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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD REPORT 825

Air Traffic Management: Support for Decision Making Optimisation — Automation

(la Gestion du traffic aérien:
aide à la décision
optimisation — automation)

Conference proceedings of the Mission Systems Panel Workshop on ATM held in Budapest, Hungary, 27-29 May 1997.

NORTH ATLANTIC TREATY ORGANIZATION

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Air Traffic Management: Support for Decision Making Optimisation — Automation

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optimisation — automation)

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Conference proceedings of the Mission Systems Panel Workshop on ATM held in Budapest, Hungary, 27-29 May 1997.

North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

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According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

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Air Traffic Management: Support for Decision Making Optimisation — Automation

(AGARD R-825)

Executive Summary

As a contribution to the increasing cooperation between NATO and former Warsaw Pact countries, the Mission Systems Panel of AGARD organized a Workshop on Air Traffic Management, held in Budapest, Hungary on 27-29 May 1997.

Emphasis was placed on the fundamentals of air traffic handling and an effort was made to establish a fruitful dialogue between experienced experts and young mathematicians, physicists and engineers, offering a fresh approach to the on-line conduct of traffic management.

The main characteristics of Air Traffic Handling were outlined; it is a large-scale, international, multidisciplinary and complex system.

The aircraft, the basic element of air traffic, was given considerable consideration: the manner in which it is flown and its dynamics, the potential role of the on-board flight management system, the current and expected level of automation, and the advent of unmanned military aircraft.

Could Air Traffic Handling become a discipline in itself as part of the academic subject of aerospace? What assistance could be made available to the human controller in the present types of operation? Finally, if it was intended to make major improvements to the management of all flights, what optimization techniques were suitable for on-line operations? These important questions were debated in a session devoted to the fundamentals of air traffic management.

An attempt was then made to illustrate some trends in the optimization and automation processes: arrivals management in the PHARE programme; application of genetic algorithms to mid-air collision avoidance; the detection and resolution of conflicts using coupled force field techniques and a broad look at global traffic optimization.

Plans and prospectives were presented: human-machine interface in the Hungarian MATIAS project; a US view of the situation as seen by the FAA; the CNS/ATM concept as an ICAO prospective and the EATCHIP-EATMS concept offered as a European perspective.

The Round Table which ended the meeting offered strong encouragement to the academic and scientific communities to inform their members of the nature, complexity and interest of the problems - numerous and varied - raised by the need to improve the presently critical air traffic situation. Examples of outstanding doctoral dissertations were included in this Workshop programme.

Gestion du traffic aérien: aide à la décision optimisation — automation
(AGARD R-825)

Synthèse

Dans le cadre de sa contribution à la coopération croissante entre l'OTAN et certains pays de l'ex Pacte de Varsovie, le Panel systèmes de conduite de mission de l'AGARD a organisé un atelier sur la gestion de la circulation aérienne, à Budapest, en Hongrie, le 27-29 mai 1997.

L'accent a été mis sur les aspects fondamentaux de la gestion de la circulation aérienne en vue d'établir un dialogue productif entre les spécialistes avertis et les jeunes mathématiciens, physiciens et ingénieurs présents. Cette démarche a permis une nouvelle approche de la gestion en ligne de la circulation aérienne.

Les principales caractéristiques de la gestion de la circulation aérienne ont été évoquées, il s'agit d'un système complexe, multidisciplinaire, international, de grande envergure.

Une attention particulière a été portée sur les avions, éléments de base de la circulation aérienne: leur pilotage, leur dynamique, le rôle possible des systèmes de gestion de vol embarqués, le niveau d'automation actuel et prévisible, ainsi que sur l'arrivée des avions militaires sans pilote.

La gestion de la circulation aérienne, pourrait-elle devenir une discipline à part entière au sein des sciences aérospatiales? Quelles sont les aides qui pourraient être mises à la disposition de l'opérateur humain dans le cadre des opérations actuelles? Enfin, si des améliorations majeures sont à apporter à la gestion de l'ensemble des vols, quelles sont les techniques d'optimisation qui conviendraient le mieux aux opérations sur ligne? Ces questions importantes ont été discutées lors d'une session consacrée aux aspects fondamentaux de la gestion de la circulation aérienne.

La conférence a examiné ensuite un certain nombre de tendances dans les processus d'optimisation et d'automation, à savoir: la gestion des arrivées dans le cadre du programme PHARE; l'application d'algorithmes génétiques pour l'évitement des collisions aériennes à moyenne distance; la détection et la résolution de conflits à l'aide des techniques de couplage des forces en jeu et un tour d'horizon de l'optimisation globale du trafic.

Des plans et des perspectives ont été présentés: l'interface homme-machine dans le projet hongrois MATIAS; une perspective US de situation comme envisagée par la FAA; le concept CNS/ATM prospectif de l'ICAO; et le concept EATCHIP-EATMS en tant que perspective européenne.

La table ronde qui a clôturé la réunion a tenu à encourager les communautés universitaires et scientifiques à informer leurs membres de la nature, de la complexité et de l'intérêt des divers et nombreux problèmes soulevés concernant l'amélioration de la situation critique à laquelle la circulation aérienne est actuellement confrontée. Des exemples d'exposés doctrinaires, de haut niveau, illustrent le Programme de cet atelier.

Contents

* Manuscript not available at time of printing

Preface

An appreciable number of symposia, colloquia, seminars, workshops, conferences and meetings are currently devoted to studies, research and developments in air traffic handling. For the period May 1993 - November 1995, at least 16 high-level public and international events were organized. In addition, the Federal Aviation Administration, the European Organisation for the Safety of Air Navigation, the European Civil Aviation Conference (with the European Space Agency, EUROCONTROL, the European Union and Member States), the International Civil Aviation Organization, the International Air Transport Association etc. organize - in addition to their specific work programmes - international conferences on general and specific aspects, a list of which (for the same period) would cover several pages.

Consequently, if AGARD were to envisage the organisation of a comprehensive workshop on this subject, the programme should be carefully selected and complement (from a scientific viewpoint for example) the current topics debated by the relevant national or international professional institutions.

The current interest in cooperation between NATO and the former Warsaw Pact European countries, together with the reservations expressed by several voices from both parties, requires careful selection of the topics to be addressed jointly. In our opinion, the efficient conduct of air traffic raises a number of questions (current problems, delimitation of control areas, development towards full automation, impact on natural resources and the environment, etc.) which justify bringing together experts from the two communities, as AGARD has done in the past within the context of NATO.

To this end, the Federal Aviation Administration (FAA) Plan for Research, Engineering and Development is currently available, as is the Studies, Tests and Applied Research (STAR) work programme of the European Organisation for the Safety of Air Navigation (EUROCONTROL). The latter is complemented by the Programme of Harmonised Air Traffic Management Research in EUROCONTROL (PHARE), coordinated and conducted jointly by a series of research institutions within the Organisation's Member States. The Future Concepts, the Very Long Term Concept Plans and the European User Requirements as defined in the European ATC Harmonisation and Integration Programme (EATCHIP) are also readily available.

The professionals involved daily in the field of air traffic have access to developments in the rest of the world via the International Civil Aviation Organization. For scientists, developers and researchers working in their (possibly theoretical) scientific environment, such contacts are definitely more difficult. AGARD's mission to improve co-operation among Member States in aerospace research and gradually extended development to the Eastern European States is another reason for bringing together scientific experts from both communities.

The selection of general Air Traffic Management topics is the responsibility of the Sponsoring Panel. The selection of a main theme and formulation of the main guidelines as well as the constitution of the programme - subjects, papers, authors, Session Chairmen - form part of the responsibilities of the International Programme Committee.

In terms of theme, this event was undertaken in support of scientific and technical studies and developments made in the context of a long-term conceptual approach. Technological achievements - actual or expected - constituted an appropriate background and provided a source of working hypotheses for further dissertations, studies and developments.

André Benoît
Programme Chairman and Editor
Mission Systems Panel

Disclaimer

The views expressed in the papers presented in this document are those of their authors. They do not necessarily reflect the policies of the Institutions to which they belong.

Acknowledgements

In addition to the gratitude expressed by the AGARD Authorities to their host country counterparts, represented at the meeting by Mr Martinusz, the Chairman of the Workshop wishes to address special thanks to the institutions and individuals who contributed to the success of this most interesting, fruitful and enjoyable Conference.

For all those involved in the meeting, the presence of General G. Alexis (Chief of Programme Coordination at AGARD), who officially opened the meeting on behalf of AGARD, was greatly appreciated.

The Hungarian Air Traffic and Airport Authorities deserve special thanks for their interest in the meeting and their active contribution to the technical programme - there was a Hungarian presentation on each day of the meeting. This excellent cooperation was certainly due (if only in part) to the efforts of Dr. Peter Moys, International Coordinator for Aviation.

The Institutions which supported the programme through active participation also deserve our gratitude:

- Académie Nationale de l'Air et de l'Espace, ANAE, Fr
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We would like to thank all individuals, observers, authors, Session Chairmen, Members of the Programme Committee, the Executive and Secretary of the Mission Systems Panel and, for this particular event, the special Programme Coordinator, Ir Carlos Garcia-Avello.

André Benoît

Theme

The present interest in cooperation between NATO and the former Warsaw Pact European countries, together with the reservations expressed by several voices from both parties, calls for a careful selection of the topics to be approached jointly. In our opinion, the efficient conduct of air traffic raises a number of questions - present problems, extent of the control, evolution towards full automation, impact on natural resources and environment, etc. - which all justify bringing together experts of the two communities, as AGARD has done in the past within the NATO world.

The Federal Aviation Administration (FAA) Plan for Research, Engineering and Development is currently available, as is the Studies, Tests and Applied Research (STAR) work programme of the European Organisation for the Safety of Air Navigation (EUROCONTROL). The latter includes the Programme of Harmonised Air Traffic Management Research in EUROCONTROL (PHARE) coordinated and conducted jointly by a series of Research Institutions of the Member States of the Organisation. Also readily available are the Future Concepts, the Very Long Term Concept Plans and the European User Requirements as defined in the European ATC Harmonisation and Integration Programme (EATCHIP).

The professionals involved daily in the field of air traffic have access to the developments undertaken in the rest of the world through the International Civil Aviation Organization. For the scientists, developers and researchers working in their scientific, possibly theoretical, environment, such contacts are definitely more difficult. Referring to the Mission of AGARD for improving the co-operation among member nations in aerospace research and development gradually extended to the Eastern European States, this, for us, constitutes an additional reason to bring together those scientific experts of both communities.

The selection of a main theme and the formulation of the main guidelines are part of the responsibility of the Sponsoring Panel. Subsequently, adequate input from possibly interested Panels - should be invited and the resulting programme should be discussed and finalized jointly with our Eastern counterparts, duly designated by the AGARD Authority.

In terms of theme, this event should be undertaken in support of scientific and technical studies and developments undertaken in the framework of a long term conceptual approach. Technological achievements - factual or expected - should constitute an appropriate background and provide a source of working assumptions.

André Benoît

Air Traffic Handling

Over the past 25 years, the Guidance and Control Panel and now the Mission Systems Panel of the Advisory Group for Aerospace Research and Development of the North Atlantic Treaty Organization have devoted part of their activities to the fascinating field known historically as Air Traffic Control, but covering most facets of Air Traffic Handling.

The Panel's contributions (listed below) cover, *inter alia*, the air and ground components considered as parts of a single system, the methods, techniques and technologies applicable to or usable for the management of the flows of aircraft and the control of individual flights, the integration of control phases over extended areas, the 4-D guidance of aircraft in critical conditions, the ever-increasing level of automation, the introduction of machine intelligence and its impact on the essential role of the human acting on-line in the control loop.

The idea of a drastic revision of the present approach to Air Traffic Handling has recently been accepted and undertaken, Doctoral dissertations do bring fresh perspectives on the air transport situation - which is becoming more and more problematic - and this report intends to encourage their authors.

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Vol. III ABSTRACTS
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Optimisation — Automation
AGARD Report R-825,
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Hungary: Home Country of the Founder of AGARD

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Dr Theodore von Kármán
(17 May 1881 - 7 May 1963)

as he addressed himself in his book *"The Wind and Beyond"* was : a Pioneer in Aviation and Pathfinder in Space, but what is more important to us, assembling here today, he was also **the Founder** of the NATO Advisory Group for Aeronautical Research and Development (**AGARD**).
AGARD has now its first ever meeting in the home country of its founder, one of the greatest scientists in aviation of our century. Let us devote this morning some minutes to the memory of this great man.

T.von Kármán was born here, in Budapest, the capital of Hungary on 11 May 1881. His father, Kármán Mór in this time was the Professor of Education at the Budapest University of Science - "Pázmány Péter"
Theodor von Kármán graduated in 1898 at the secondary school, in the famous "Minta", a Model Gymnasium which his father had founded. "The Minta" gave this world such excellent men, like Prof. Dr. Thomas **Balogh** of Balliol College in UK or Prof. Nicholas **Káldor** of the Kings College at Cambridge. Leo **Szilárd** of Columbia - *who wouldn't know this name-* and the Nobel Prize winner György **Hevesy** from Denmark graduated in this famous school too.

After the secondary school T.v.Kármán enrolled for courses at the Royal Joseph University of Polytechnics and Economics - Budapest. He finished here his studies and graduated in 1902 as an eminent with distinction.
After a few years with the Artillery of the common Royal Austro-Hungarian Army where he was to serve as "a volunteer for the King", von Kármán returned to the Royal Joseph University to be the Assistant of Professor Donát Bánki, who improved the first carburetor for Otto motors. Also he was the first to use water injection in internal combustion engines to protect the walls of the cylinders from overheating. This is now a common method in the airplanes' jet engines. Prof. Bánki was a very good practical engineer and inventor of his age, but he was interested rather in practical problems to solve, than in the theory of the natural phenomena. So the young von Kármán applied for a fellowship of the Hungarian Academy of Sciences for traveling abroad. This way went he to Göttingen in Germany in October 1906 for two years.
In March 1908 he arrived at Paris, where he listened the lectures of Madam Curie at the Sorbonne. He was present at Issy-les-Moulineaux in August 1908, when Wilbur **Wright** made his first flight in France. It was still in this year that von Kármán received the invitation of **Professor Prandtl** to return to Göttingen to cooperate in the development of the rigid airship "Zeppelin" Here was built the first wind-tunnel in the European continent. In 1908 and 1909 Frederick William **Lanchester** paid visits to Göttingen and explained his theories on the "peripteral motion (the vortex) and on "forced waves" in aerodynamics. F.W. Lanchester made a great impression on the young scholar von Kármán. Later in his book, published in 1916, Lanchester urged *the need for a worldwide cooperation in the research in aviation.* This hit a responsive chord in Kármán and gave him the impetus when later in 1952 - just **45 years ago**- he proposed the **establishment of AGARD**, NATO's aeronautical research arm.

But back to 1911 when Prof. Prandtl in Göttingen let published Kármáns' theory on the vortex. This discovery became known later as the "Kármán Vortex Street".
In 1912 von Kármán arrived at Selmeczbánya, Hungary -(now this town is belonging to Slovakia) where he took over his Chair of Applied Mechanics at the venerable mining academy founded in the eighteenth century. Soon after that a vacancy occurred in Aachen and von Kármán went there to occupy his intellectual base for the next 16 years as Professor at the Aachen Technische Hochschule , the center of mining and metallurgical engineering. There he met - among others - also Prof. Hugo **Junkers**, who was in one person also one of the greatest airplane designers and manufacturers of this time in Germany.
In 1913 v. Kármán began to build a wind-tunnel in Aachen, which he successfully completed in 1914. In this year in cooperation with Erich Trefftz they worked out the mathematical model of the different wingshapes
Professor von Kármán also took lessons of practical flying at Köln military airfield.

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

In Fall 1914 von Kármán received an official seal of the Army to report to the 61st Royal Fort-artillery Regiment as First Lieutenant in reserve. In August 1915 the German General Staff was seeking for the scientists and technical experts in aeronautics to help with the further development of German heavier-than-air craft. In pursuing aviation experts to help them in this mission, the German authorities learned that Dr. von Kármán served in the Austro-Hungarian Army and they sent a letter to the Ministry of War -Kriegsministerium in Wien. Dr. von Kármán from his station at Budapest was ordered to report in the Kriegsministerium. There he was told of the German request.
"Then I am to be transferred to Berlin" - said First Lieutenant von Kármán unhappily as the commanding officer finished with the letter.
"Not at all my dear Kármán" replied the colonel , stroking his mustache. *"Since the Germans want you, you must be pretty good! You will remain in Wien! We are setting up a department for aviation and we can use you here."*
So for the remaining time of WWI. Dr.von Kármán served the K.u.K Army in Fischamend, a small town near Wien, where the experimental laboratory of the K.u.K. Luftfahrttruppe (Air Force) was set up. The first task for Dr.von Kármán was to design and built up a large wind-tunnel for testing propellers in an airstream. Later in 1917 he started there also some pioneer helicopter experiments. Dr. von Kármán assisted by too designers Asbóth and Zurovecz, developed a "captive helicopter" for observation and this machine was the first of this kind all over the world!

Theodore von Kármán returned to Aachen in November 1919. Since the Versailles Peace Treaty forbade to Germany to plan and to build motor driven airplanes, the German students founded the Flugwissenschaftliche Verein Aachen (FUA) and started to construct sailplanes. Professor von Kármán gave them support in the design of the gliders.

In 1926 Dr. von Kármán received an invitation from Dr. Robert Millikan from the California Institute of Technology (CalTech) at Pasadena. Here he gave advises and help for building - again a wind-tunnel, - the first one in the States. In this year he visited also Japan. The journey in 1926 was von Kármáns first trip to his second home country , where he spent later his most active time as a leading scientist in the History of Aviation. In 1928 Dr. von Kármán returned to the CalTech to see the preparatory works of the wind -tunnel.
In July 1929 Dr. Millikan reiterated his offer to Professor von Kármán to be the Director at the Guggenheim Aeronautical Laboratory in Pasadena. In December 1929 Dr. von Kármán occupied this post and took Frank Wattendorf as his Assistant with him. Until 1933 he visited back to Aachen from time to time. In 1934 he paid his last visit to Germany before the end of WW II.

In 1935 T. von Kármán was applying for an American citizenship and he had carefully prepared himself on the United States' history and on the Constitution. When he appeared at the Court , the judge said: *"So , you are Professor von Kármán ! I read about you in the papers. Tell me, what happened with the Macon* (USS Macon was an American airship which on February 12, 1935 met with a catastrophe.) The Professor explained the phenomenon of the occluded weather front, the judge listened intently then nodded. Without further questioning he asked the applicant to hold up his hand and Dr. von Kármán was sworn in. He never did get a chance to show off his hard-won knowledge of the History of the United States.

As Dr. Robert Millikan had foreseen, the year round temperate climate was attracting airplane manufacturers to Southern California. Douglas was already well established in Santa Monica in the 1930's. Lockheed had opened up shop in Burbank and Consolidated Aircraft (predecessor of Convair) was building its complex in San Diego. The CalTech and Professor von Kármán took an important role, a prominent part in the development of the airplane manufacture. This was the kind of thing they had been waiting for - an opportunity to provide facilities for the airplane industry and to see CalTech grow as it helped the new industry grow. Some of the first tests were actually paid for by the Guggenheim Foundation, since the industry had not yet clearly seen its role in sponsoring research. The first major problem they solved was the quite serious vibration caused by the turbulence created between the wings and the fuselage on DC-1 and DC-2 type airplanes.. The sharp corner where the two came together caused the air to decelerate as it swept past and to form eddies. As these eddies broke from the trailing edge of the wings, they hit the tail, the stabilizer and the elevator, causing them to vibrate. Such buffeting, if allowed to appear above a certain airspeed could easily throw the airplane out of control !
To study eddy formation, especially the Kármán Vortex Street, was the main field of interest of Professor von Kármán. The solution proved to be very simple for the Professor, after some tests in the wind-tunnel. It was to apply a small fairing to the junction of the fuselage and the wing. This device created a striking change in the airplane's behavior. The air eddies smoothed out and the tail no longer shook. It was a remarkable example of how a wind-tunnel could be applied in a practical way to save an aircraft. Later, DC-3 went into

production at the end of 1935 and began its long carrier as the workhorse of aviation.
In Pasadena the Professor opened the doors of his house to his colleagues, students and other visitors, among them the world's most famous scientists of that time, like Niels **Bohr**, Enrico **Fermi** and Albert **Einstein** as regular visitors. In the middle and late thirties this world saw an enormous growth in aviation and Professor von Kármán took his share in this extraordinary development. Beyond receiving fellow scientists in his house, he traveled pretty much to see and experience the developments in the rest of the world out of California.

The Fifth Volta Congress of High Speed flight in Rome in 1935 was the first serious international scientific congress devoted to the possibilities of supersonic flight. All of the world's leading aerodynamicists - among them our Professor von Kármán -were invited. This meeting was a historic one, because it marked the beginning of the supersonic age. It was the beginning in the sense, that this conference opened the door to supersonics as a meaningful study in connection with flight and secondly because most developments in supersonics occurred rapidly from then on, culminating in 12 years later - on <u>October 14th, 1947 - in Colonel Charles Yeager's piercing of the sound barrier with the X-1 airplane, in level flight.</u>

In 1937 his former Assistant Frank Wattendorf invited the Professor to Peking, to inspect the new aeronautical engineering department at Tsing Hua University, China's leading technical school. On his way to China, he visited also Moscow, where he was shown the laboratories of the Central Aero-Hydrodinamic Institute (ZAGI).
On July 23, 1937 Professor von Kármán, accompanied by Frank Wattendorf left China for Japan, where he was scheduled to lecture at Tokyo Imperial University.
Returning to the States Professor von Kármán found himself introducing his scientific experiences into a variety of new industrial fields, ranging from turbines to wind mills, which had never before considered the science of aerodynamics as useful to them.

Then one day in 1939, General Henry (Hap) Arnold, head of the US Army Air Corps called Professor von Kármán to attend a meeting in Washington. There the General indicated his strong belief that the U.S. Army Air Corps could not reach the top in aviation and remain there without doing experimental work to advance this art. He wanted to hear Professor von Kármán's opinion on what facilities the Air Corps needed to make a major advance in flight.
"General - the Professor said, without hesitation- *in my opinion the first step is to build the right wind-tunnel. It should be large enough to contain a full scale airplane engine installation and should be capable of generating winds of at least four hundred miles per hour."*
"That's exactly what we do want - replied General Arnold. - *the highest combination of speed and size."*
So the General authorized a contract for the design of a 20 foot, 40.000 HP wind-tunnel, the first of its kind for Wright Field.

In 1939 F. Wattendorf went to Wright Field and remained there in charge of design and construction for the two years, it took to build up this huge , fantastic structure. More importantly it started the U.S. Air Corps on their own experimental program. It also was the very beginning of a great and faithful association between Professor von Kármán and General Arnold, and subsequently the US Air Force.
Later the Professor consulted with Boeing and together with Prof. Markham they worked out the design of what was then the U.S. industry's largest high speed wind-tunnel. It reached the speed of sound. Boeing representatives later declared that this tunnel greatly influenced the development of such famous aircraft as B-47, B-52 and later the B-707.
During the WWII. Prof. von Kármán became a consultant to the Army Bureau of Ordnance. In these years high-speed developments moved a quickened way, especially in propulsion. Still in 1941 Gen. Arnold saw the first turbojet plane flying in England, powered by engines developed by Sir Frank Whittle. He immediately ordered jets built in the United States. The first US manufactured jet plane flew on 1st October, 1942.
It was then in early 1943 when the US Air Force began to consider supersonic flight in a serious way. Brigadier Gen. Franklin O. Carrol, the Chief of the Engineering Division at Wright Field invited Professor von Kármán to Dayton on a week-end and there he put a <u>simple</u> question to our Professor:
"Would it be possible to build a supersonic airplane capable of flying at Mach 1.5, 1000 miles an hour?"
Here in this <u>simple</u> question was the culmination of all the theory and speculation on supersonic motion and flight in which Professor von Kármán had been involved since almost the turn of the century! It was the first time that a practical question of this kind had been put to him. Had theory and technology arrived at the point where one could set a practical project into motion?
Telling the General he would think about it, the Professor returned to his hotel in Dayton and he arranged with the General to call in a few engineers from Wright Field. Spreading the papers on the floor of the hotel room, they worked all day Saturday and all over next

Sunday. On Monday Professor von Kármán returned to Wright Field. In his case he took a preliminary design with the main data on span, strength and weight of the plain he dreamed. He placed the papers before General Carrol and his aides.
"*Yes* - the Professor told them - *it is quite practical to build a plane that can fly at a speed of thousand miles an hour."*
Later the Professor discovered that the General used his first, rough design as the basis of a major decision, resulting in 1947 in the famous Bell X-1, the first plane to pierce the sound barrier in level flight.

In July 1944 his old friend General H. Arnold called the Professor.
"*What do you wish me to do, General*" - he asked.
"*I want you to come to the Pentagon and gather a group of scientists who will work on a blue print for air research for the next twenty, thirty, perhaps fifty years.*"
This was quite a challenge and the Professor accepted it.
Soon after the Scientific Advisory Group was set up and some three dozen leading scientists and engineers joined the Group. General Arnold himself briefed the Group at their first meeting:.
"For twenty years the Air Force was built around pilots, pilots and more pilots..." -he said. "The next Air Force is going to be built around scientists - around mechanically minded fellows"

In 1949 General Hoyt Vandenberg, Chief of Staff of the US Air Force asked Professor von Kármán to study the role of research and development in the Air Force from an organizational point of view. In his report "Toward new Horizons" the Professor made his recommendations for the improvement of cooperation between the Advisory Group and the General Staff. Also in this report he mentioned, that putting up an artificial earth satellite was well within existing technology!

In April 1947 the birth of NATO, as a defensive alliance against the expansion of the Soviet Union, was published in the media. Also a new idea was born in mind of Professor von Kármán: why not set up for NATO a Scientific Advisory Group, similar to the one of the US Air Force?

The first move was to forward a memo to Mr. Robert A. Lovett, the Deputy Secretary of Defense. He suggested the Professor to go to Paris to confer with General Gruenther, Supreme Commander of the Allied Forces in Europe.

General Gruenther favored the idea, but suggested to limit the Group's activity initially to aeronautics, rather than try to cover all the sciences as they bear on military planning. This was agreeable to Dr. von Kármán.

In the next few days the Professor and his associates made plans and in February 1951 twelve NATO nations were invited to a conference at the Pentagon. Representatives of eight nations showed up. At the meeting the Professor explained the idea and basic purposes of a scientific advisory group. The meeting worked out and adopted a proposal to the high command of NATO on the formation of the NATO Advisory Group for Aeronautical Research and Development (AGARD)

In pursuance of some high level debate, in February 1952 AGARD was approved and the Professor throw himself into the job of setting up really the organization, what he dreamed about.

The Professor stated in his book:

„AGARD is young as international organizations go, but it has already given us valuable lessons in international cooperation, especially among the small nations." This was written 34 years ago and the history of this three and a half decades is another tale, it is a part of your life.

I wish to close this commemoration recalling the ceremony on the morning of February 18, 1963 when Professor Theodore von Kármán , then the world's greatest aeronautical scientist, was awarded an honor never before bestowed on an American scientist - the nation's first National Medal of Science. Von Kármán at eighty-one had been selected over scores of candidates for his still unexcelled range of unique contributions to engineering, science and education.

President Kennedy was to present the golden medal to Dr. von Kármán. When the President arrived at the Rose Garden of the White House von Kármán. stood there surrounded by friends from all over the world. Then the group of the festive party moved to the reception area. Shuffling along on arthritic feet, the Professor paused at the head of the staircase as if in pain and the young President quickly moved to his side and took his arm. Von Kármán looked up at the President and gently shook off the proffered aid

„Thanks Mr. President, - he said with a wan smile, - „One does not need help going down, only going up".

Ladies and Gentlemen, now here in Budapest you may gain your own impressions about the country and people of the founder of your Group - AGARD. My colleagues will present you detailed information on the airspace organization and on the Human-Machine Interface of our project MATIAS - the Magyar Automated and Integrated ATC System.

DYNAMIC CONTROL OF AIR TRAFFIC
Criteria - Control variables - Constraints

GENERAL INTRODUCTION

by

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In a recent presentation, Dominique Colin de Verdière* considered which areas of air traffic handling need to be optimised. The question is not only pertinent, but must be answered if we are to meet with the intention of turning our attention to the same areas.

Several optimisation and automation aspects will be discussed in the course of this Workshop. In this general introduction, the intention is simply to outline some essential and basic problems concerning the conduct of air traffic.

Imagine the European area without geographical state boundaries -which even today impose severe constraints on or limitations to the integration of control- and consider all the flights taking place in this area.

The following flight categories may be identified in such an area :

- flights conducted entirely within the area;
- flights initiated within the area, but ending outside;
- flights initiated outside the area, but ending inside;
- flights initiated and ending outside but crossing the area.

For flights initiated and/or ending in the area, the path of the aircraft inside the area can be considered partially (from brake-release (or) to touchdown) or, ideally, in its entirety (from departure gate (or) to arrival gate). In the first instance, the aircraft path includes all or part of the flight phases. In the second case, it covers both the flight path -all or part of the flight phases- and ground movement.

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To what extent can ground movement and the flight phase be decoupled ? What would be the impact of a decoupling on overall ATC performance ? This, of course, would depend on the performance criteria selected but it is clear that today no one could answer this question consistently. Nevertheless, in this first session there will be a paper on this difficult subject presenting a State-of-the-Art Review and Perspectives of the Dynamic Control of Ground Movements.

If the optimisation process intends to cover aircraft movement from brake-release to touch-down, or to exit of the area, or from entry to touch-down, or from entry to exit, as applicable, a detailed knowledge of the aircraft capabilities and careful control of the aircraft trajectories are necessary.

For each flight, there is an optimum trajectory deriving from either the operator's criterion (comprising time, consumption, and cost) or possibly constraints imposed by society (conservation of natural resources, noise abatement, minimum atmospheric pollution by chemical emission). This optimal or preferred trajectory is essentially expressed in terms of speed versus altitude profiles, given the prevailing geographical and meteorological flight conditions.

Currently, the flight could easily be conducted in such optimum conditions, even in a fully or quasi automatic mode, but only if it were the only aircraft in the sky. This will be discussed in subsequent presentations.

In reality, ATC authorities have to manage a considerable number of aircraft. Then, when an aircraft enters the control area, it will be allocated a trajectory whose profile corresponds as closely as possible to its preferred trajectory, but in such a way that it does not interfere with neighbouring traffic. The relevant profile should be selected from a global criterion based on economy and/or environmental protection and conservation of natural resources.

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

Avoiding interference with other traffic entails the assurance of standard safety separation, both horizontally and vertically, and compliance with landing separations.

Conflict avoidance (usually local and of short duration) can either be included in the plan when the aircraft enters the system, or left in for subsequent resolution action, depending on the level of automation desired. This will be illustrated in some practical examples presented later in this Workshop.

The landing separation matrix providing distance separation between given categories of aircraft is used to generate time separations between arriving aircraft at the runway threshold.

The set of control variables may differ for the various categories of flights. For all categories, the speed versus altitude profile provides an essential set of control variables, probably the most important set for those flights ending in the area. For flights initiated inside the area, the departure time -at the gate or at brake-release- within a limited time interval is also included in the set of control variables. Limited variation of cruise altitude and moderate displacement in the horizontal plane will also be required for conflict resolution.

A set of specific trajectories will be derived from:

- the global criterion adopted,
- the method/techniques used to achieve optimisation,
- the best sets of information available on-line.

These trajectories then have to be implemented and some of their critical aspects will have to be retained, in spite of all the disturbances which will occur. The conduct and control of the relevant flights can now be achieved with great accuracy, using either a flight management computer which is ground-based -as developed for the Zone of Convergence (ZOC) or similar control techniques- or integrated in the aircraft avionics.

Despite clearly complementary aspects, the two approaches generate debates reaching almost philosophical proportions: controllers see everybody and should remain in control of all aircraft movement! the sky will become wide open and free flight is possible now !

This last remark will certainly constitute a reasonable starting point for our main discussions, including :

- The automatic aircraft and the unmanned air vehicle: are they compatible with present air traffic management or do they require a fully automatic air traffic control system ?

- The Flight Management System:
  Is it likely to become the panacea, the essential tool which opens the sky well beyond the classic routes or are we fooled by the manufacturers advocating its use ?

- Furthermore, can we envisage part -and, if so, which part - of traffic regulation being conducted on-board. What would be the respective roles of the air-based and ground-based control/regulation components ?

To have any hope of success, the various concepts cited in such discussions need to be approached with a fresh perspective, with a mind unbiased by present operational methods.

This is one of the reasons why great hopes are placed in the work undertaken at postgraduate level to produce theses in what is becoming a fascinating new multi-disciplinary field open to numerous kinds of studies and research and development programmes. Outstanding examples of this co-operative academic/operational effort will be given in the course of this Conference (see Durand, Zeghel , Trivizas, etc.).

To all of you, we offer our best wishes for a very successful Conference.

DYNAMIC CONTROL OF GROUND MOVEMENTS

State-of-the-Art Review and Perspectives

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1 Summary

Air Traffic Management is a very complex and challenging domain. To cope with future traffic demand, while still maintaining or even increasing safety and efficiency of air traffic operations, intelligent machine functions have to be developed to assist the human operators in their mental control tasks. The specific requirements of the ATM domain necessitate sophisticated and well-designed assistance tools. Their most significant characteristics, design principles and structures are discussed and examplified in a real-world application.

2 Introduction

The approach to handle future air traffic with increasing traffic density, very complex air traffic management and control functions and an increasing demand to manage air traffic operations more efficiently and economically, is to support the human Air Traffic Control Operator by intelligent machine functions for *situation assessment*, *diagnosis*, *planning* and *decision-making*. Computers should not only do "simple" information processing but should often also take over human cognitive abilities. In many applications a desired behavior of the *world*[1)] should be achieved by a "real-time plan-based control" (see e.g. /1/).

3 Management and Control of Complex Systems Based on Dynamic Planning

Most complex systems can only be managed/controlled if future consequences of actions are taken into account. Skilled human operators normally try to predict the potential future systems behavior by using an internal model of the control task, whereby they are able to consider uncertain as well as incomplete information. But in unexpected strange situations, that require a fast reaction, the human operators interrupt their mental planning and focus their attention on the present control task to achieve a safe situation. This skillful human behavior suffers when the operator is over-loaded with information and the operator's information processing cannot follow system's dynamic.

Although a computer can process a much higher data volume, a technical copy of the human property of being capable of fast reaction (by switching the internal control structure) is also necessary as well as the ability to plan under uncertainty. For that purpose figure 1 shows a suitable, general, three-level architecture, which can be derived from a functional decomposition of a generic closed-loop decision making system /2/ (fig. 1).

The system to be controlled is situated on the basic level. In the ATC domain it can be a certain traffic area (e.g. an airport) with an underlying structure (e.g. a network of taxiways and runways) containing a changing set of aircraft. On this level the dynamic behavior is described by a time-variant state vector (e.g. vector of aircraft positions, speeds, etc.)[2)] and is affected by the environment (events, disturbances) as well as by (re-)actions (e.g. controller instructions and commands, given guidance signals).

A computer-supported control requires a state measurement that usually does a low-level kind of information abstraction by suppressing fault sensor information or by calculating "artificial" states in case of lack of sensor information, in order to present full state information. Further decision support can be given by offering information about the environment that will have an influence on the system in future.

In order to realize a plan-based control further abstraction is necessary since planning can only be done in reasonable time if the model of the *world* has a suitable granulation. The result of this abstraction process is a time-variant *situation* that is assessed permanently[3)] and that is explored in the plan generation process which is started under certain conditions. *Situation* information might be delivered to the human machine interface, too. *Situation assessment* is based on the results of the monitoring process, checking the conformance between planned and actual *situation*, but goes beyond that by exploring the "severeness" of detected present and future differences in order to give necessary information for a suitable mode selection. For such switching of control structure it is necessary to consider *situations*, information (predictions) about relevant future events, if available, but also previous plans. Thus a further information loop exists.

1) the technical or environmental system which is controlled

2) The state vector might contain qualitative information (e.g. weather conditions) that cannot be measured but that are observable by the human operator just as a part of the quantitative states (e.g. aircraft which can be seen by the tower controller looking through the windows).

3) The term "permanently" should be interpreted as " done highly frequent".

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

When an actual *situation* is assessed as "critical" since it causes an *actual conflict*, the human operator is provided with *conflict information* (e.g. aircraft which causes the conflict; involved aircraft; location). Under such circumstances a further decision support can be given by an automatic conflict resolution function[1)] that immediately influences the system (e.g. by using guidance signals) and/or proposes the right sequence of (re)actions in order to resolve the situation. However, under most operational conditions actions can be drawn from plans.

It should be remarked, that such an hierarchical organized control should not imply a master-slave principle, since the human operator must have some means to have an influence on the planning according to his intentions /3/. This kind of information feedback is not shown in fig. 1.

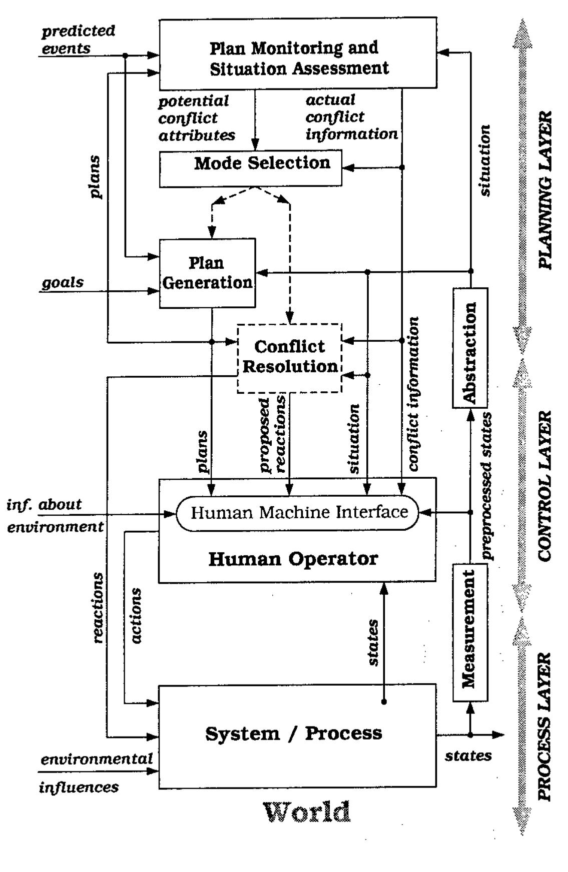

Fig. 1. A general architecture of an "intelligent", plan-based management and control

4 Planning Problems and Basic Concepts

In a common sense planning can be described as the task to determine the actual and future interactions with the *real world* to reach well defined goals. This can formally be expressed as the search for a transformation with *operators* or actions from a known *state* into another *state*, which satisfies the *goal descriptions*. It is clear that formal descriptions of *states* and *operators* are needed, too.

In the domain of airport surface traffic management there are other important problems which are related to the required safety level. Because of the continuous traffic at major airports it is not practicable to alternate between planning and implementation of a whole plan. Instead planning and implementation must be interlaced. Of course, in this domain planning has to be based on a permanent plan monitoring to realize a closed information loop. The use of planning as an intelligent, look-ahead, closed-loop control (*reactive* or *dynamic planning* /4,5/) presupposes the solution of the following problems:

- ☐ planning under uncertainty, and
- ☐ planning under real-time demand.

These problems will be described in more detail in the next sections and also some general approaches will be given.

Of course, the design of the system as well as the accommodation of the present operational procedures to such a system have to be done in view of the controllers' acceptance and their workload. These aspects have an backward effect not only on the HMI[2)] design but on the planning algorithms, too. Some questions about the controllers' ability to exercise influence on the planning and the proper plan representation are answered in another section.

Since *dynamic planning* with information feedback is not sufficient to fulfill all requirements, another important planning principle, that is termed as *recurrent planning with sliding horizon* is necessary which is covered in last section of this chapter.

4.1 Uncertainty

4.1.1 Reasons for Uncertainty

If consideration is given to what information is necessary to describe a *state*, the chosen set of measured signals from the *world* and their derived values to extract the relevant information must be listed. But, the actual available knowledge about

- ☐ the intentions of the *agents* (aircraft controlled by pilots) according to their plans (the taxi-instructions given by the controller),
- ☐ the predicted future events which will influence the behavior of the *world* (the inbound traffic etc.),
- ☐ the actual and known future operational conditions, constraints and goals

1) Automatic real-time conflict resolution is not necessary in all applications.

2) Human-Machine Interface

also belong to a description of a *state*. It should be noted that for all types of information there are different degrees of certainty. For instance, in spite of the unavoidable errors in measurement, the actual position of an aircraft is "better" known than the predicted touch-down time of an arrival. Beyond that, it is clear that the uncertainty of any predictions will increase with an expanding time-horizon.

For that and other reasons, such as the human involvement, the limited accuracy of measurement, etc., any model is not able to copy the dynamics of the real *world* without errors. Thus, the uncertainty is caused by (a more detailed description is given in /6/:)

- ☐ the inaccurate assessment of *world* signals,
- ☐ the inaccurate and erroneous prediction of future events,
- ☐ the inaccurate modeling of the *world*.
- ☐ the uncertainty about future operational conditions, constraints, goals, etc.

Now some general approaches for planning under uncertainty are discussed, which are also used in the TARMAC[1)] /7,8,9/ planning system, developed by the German DLR.

4.1.2 Planning with Time Intervals

If the *world model* is characterized by continuous time variables it is often useful to use time intervals for planning, which was introduced by Allen /8/). This allows to include the uncertainty of the prediction about the exact time of an event in the planning process. The size of the time interval, within which the predicted event will happen, can usually be determined according to on-line statistics or the probability density functions of estimated model parameters (to predict an event). Otherwise a "fit" size has to be assumed "per definition" (this problem is discussed later).

If events are related to time intervals, then a *world model* is needed which is able to extrapolate the intervals into the future. In general this leads to two possible views (fig. 2):

- ☐ a resource is always used by/allocated to an agent for a certain duration (at every certain location the aircraft may be there for a certain duration),
- ☐ at every certain time an agent may use several resources (at every certain time an aircraft may potentially be at several locations).

If furthermore the inaccuracy of the model is taken into account, the sizes of the intervals will increase with time according to the growing uncertainty (lowest and highest expected speed of an aircraft). A better interpretation can be obtained if the durations[2)] for the use of a resource according to the *dynamic world model* are extended through *buffer intervals* (against uncertainty) on both sides (fig. 2). Such an extended interval shall be called *occupancy interval* (**I**).

[1)] Taxi And Ramp Management And Control

[2)] which are needed by an aircraft to pass certain taxiway sections of a certain taxi path

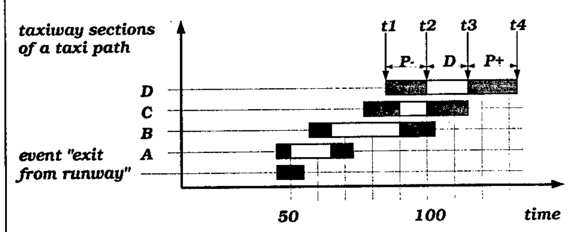

Fig. 2. *Occupancy intervals* and their expansion caused by the increasing uncertainty

The figure shows the extension of the planned resource allocation time intervals and their expansion caused by the increasing uncertainty illustrated for the example of the taxi-path planning. Let the taxi path of an aircraft be *A-B-C-D-...* , where *A, B, C, D,...* are the consecutive taxiway sections of the taxi path; D_A, D_B, D_C, D_D, ... the corresponding durations (for this aircraft); t_0 is the present time, $t_S = 50$ the predicted time when the aircraft will start its taxi operations (for instance the predicted runway-exit time); $t_P \leq t_0$ the time when the prediction was made, and $\varepsilon_0 = f(t_S - t_P)$ the (assumed or calculated) uncertainty interval for this prediction.

However, planning of an occupancy of a certain resource for an interval **I** according to the known/assumed uncertainties leads to two additional problems which have to be solved:

- ☐ The ε-Parameter Tuning Problem
- ☐ The Conflict Evaluation Problem

4.1.3 Plan Monitoring and Situation Assessment

4.1.3.1 Basic Considerations

Any *reactive planning* has to be based on a permanent or repetitive /5/ comparison between the *state* of the *real* and the *planned world* at the present time. This can be called *plan monitoring*.

First it should be noted that not every difference between the planned and the real *state* is discernible, because

- ☐ there is always a limited accuracy of the measurement of the *world* signals, and
- ☐ there might be a certain granulation of the *world model*, which is used to describe the planned *state*.

However, even a recognized difference between the *state* of the planned and the real *world* does not inevitably mean that re-planning is necessary. For the judgement whether planning should be done, the planning system must contain a "look-ahead unit" /10/ which extrapolates the *actual world* into the future considering the remaining *operators (acts)* of the present plan. This can be done better one abstraction level higher than the *state-level* - at the so called *situation-level*. Therefore any *situation* assessment requires the prediction of the future *states* of the real *world*.

In the ATC domain usually an *actual conflict* is caused by a pilot violating his/her plan, that means he or she does not follow the instructions of the controller.

One example is the deviation of an aircraft from the instructed taxi path. A more general consideration of an *actual conflict* must include all circumstances that require an immediate action by controllers (commands, warnings etc.) and pilots of the certain aircraft or the set of involved aircraft. The detection of such rare conflicts is of great importance, but not the only task of *situation assessment.*

Under "normal" operational conditions one has to expect a frequent non-conformity between planned and actual *situations*[1]. However, even in case of non-conformity adaptation of plans is not necessary as long as it is or seems to be sure that neither the *world* will be led into a critical situation nor any goals will be lost. But often the *situation* should be assessed as a *potential conflict*, that means there is a certain chance that planning is or will be necessary in the near future in order to generate proposals for suitable actions.

Since there is no objective "belief measure" and hence it is not obvious whether planning process should be started, there is another objective of *situation assessment* to give some clues to the plan generating unit to answer these questions. So, besides detection of *actual conflicts*, a suitable evaluation of *potential conflicts* is required.

The result of the *plan monitoring* and especially of the evaluation of a detected difference between the planned and the real *world* should be a classification of three categories:

- ☐ The difference is tolerable that means no *conflicts* were detected.
- ☐ The present *situation* requires a replanning immediately or at a later time (this point is viewed in the following section).
- ☐ The *situation* is crucial (runway incursions, deviations) in the sense that it requires an immediate reaction by the system (guidance signals) and/or by the controller (commands to the involved pilots). So, first of all the present *situation of the world* has to be transferred into a safe *situation* without planning which then later will allow a normal time-consuming planning.

The evaluation of possible future conflicts through the *situation* assessment should be based on the same considerations as pointed out above. Finally it should be mentioned that the monitoring task can easily be decomposed and distributed to several monitoring processes (units) corresponding to the involved aircraft and/or specific topological elements (taxiways, junctions, areas etc.).

[1] In many cases the planning process does not calculate future (planned) *situations*, but a sequence of actions. Giving a certain *initial situation*, a planned sequence of actions, and the actual *situation*, the monitoring process is able to detect whether the actual behavior of the *world* differs from the planned one or not.

4.1.3.2 Determination of the Planning Necessity

The correlation between an increasing *planning horizon*[2] and the increasing uncertainty already has been explained. This bears the thought that automatic planning should be done as late as possible to limit the *planning horizon* as much as feasible. "As late as possible" means there is enough time to compute a sufficient plan, but also enough time for the involved humans to accept/understand and possibly to transmit the plan.

But there is a second aspect, which also has an influence on the determination of the *planning necessity*, and which relates less to uncertainty but rather to the quality of the best plan. If the plans for the agents (aircraft) are made in the same order as the agents become known (or have to be replanned as the result of *plan monitoring*), the limited resources are assigned to the agents in the same order, too. This "first-come-first-served" method is equivalent to a non influenceable ranking of the agents involved in the planning process. Therefore a skillful ordering might influence the quality of the plans by grouping some agents and computing their plans at the same time and/or (if the planning task becomes for complex) by determining a subset of aircraft which should be planned first.

4.1.3.3 Situation Assessment in Real-Time

As explained in the previous section, planning functions are based on situation assessment working permanently. So it is clear that it has to be done rapidly in order to achieve a highly frequent recurrence. Since detection of actual conflicts is one objective, situation assessment has not only to be performed fast but under well defined real-time conditions.

A very promising approach to this need is the decomposition of situation assessment in sub-tasks which then can be executed in parallel if a network of computers is available. Beyond that, this possibly bears the advantage of being a rather fail-safe solution. Decomposition of situation assessment should utilize the circumstance that monitoring can be focussed on aircraft as well as on areas.

Figure 3 shows a system performing parallel situation assessment that consist of:

- ☐ a variable set of aircraft monitoring processes A_i,
- ☐ a fixed set of area monitoring processes N_k,
- ☐ a supervisor process, that controls aircraft and area monitoring processes and performs conflict detection (D) as well as conflict evaluation (E),
- ☐ a knowledge base that serves as a data interface, too.

Each process A_i observes the movement of the aircraft i and predicts its occupancy intervals for all sections of its taxi path that are delivered to the potential conflict evaluation process E. Furthermore it proves whether the aircraft is still able to execute the next planned action,

[2] *Horizon* means depending on the context either the farthest future time, up to which is planned, or the duration from the present to this time.

for example: whether the aircraft is able to stop (as planned) or is able to turn into the required taxi way etc. Such information of short-time prediction is given to the actual conflict detection process D.

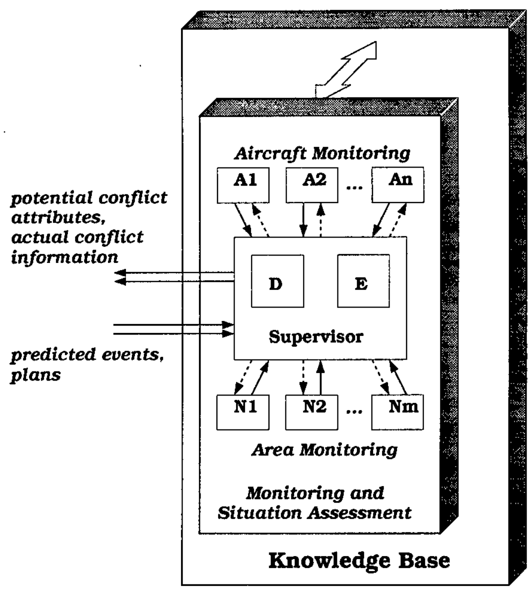

Fig. 3. Architecture for real-time situation assessment

Every process N_k monitors the compliance of the planned taxi paths and crossing order(s)[1] of all aircraft moving on area k. Deviations of aircraft from the planned taxi path are always actual conflicts, whereby predicted changes of the crossing orders are assessed as potential conflicts since they might be tolerable with respect to the planning goals.

4.2 Real-Time Demand

Real-time demand leads to the most difficult problems in the field of automatic planning. Although a lot of work has been done under several perspectives it seems there is no general solution especially for complex domains like ours.

Control in complex systems is in general hierarchically organized. From the lowest layer up to the highest layer the degree of abstraction rises as well as the considered time horizon. The specific task of each layer has to be solved under given constraints by the superior one /11/.

For automated direct or tactical control at the lowest layer (e.g. in the aircraft control systems) a common agreement exists about the meaning of the term "real-time". The control task (value computing of the control variables, handling of exceptional cases, etc.) has to be finished within a certain period. An appropriate duration of the period can usually be assessed by analyzing the system's dynamics. Since the computing normally is simple even for highly sophisticated control algorithms, a worst case study of the time consumption can be done.

However, these statements cannot be applied directly to planning tasks on higher layers. The most important reasons for this are:

- An appropriate duration of a period in which any planning process should terminate cannot be fixed a-priori. Only the latest time can nearly be settled (regarding to a corresponding future event) when the planning process should finish.
- During a planning process the *world* cannot be assumed as invariable. Even cases have to be covered, where an ongoing planning has to be cancelled automatically and restarted, because the start conditions are no longer valid (*non-monotonic planning*).
- Planning is a very complex task which incorporates several sub-tasks, such as *plan monitoring*, determination of the *plan necessity time*, *single planning*, etc., which have different time demand.
- Sometimes humans are involved in the planning process.

This is a much worse situation than in the context of direct control. The main questions are:

- How can the planning process be speeded up ?
- How fast must the planning process run to ensure that the time demand problems can be solved ?

There are two main options which might be useful to speed up the planning process.

1) Whenever possible the planning task should be decomposed and be distributed to different planners. This can be done horizontally or vertically.

   - A horizontal decomposition means to split the planning tasks into smaller, easier and faster solvable tasks so that the aggregation of all partial plans solves the original planning problem. The decomposition should be oriented on the natural structure of the *world* for instance, different planners for the different aircraft or different areas of an airport. Of course, by doing this, a lot of difficult unsolved problems have to be solved, which are related to such fields like *distributed planning*, *multi-agent planning*, and *cooperative planning* /12/.
   - If the decomposition is realized in such a way that there are several layers of abstraction /13/ it is called "vertical" and leads to the concept of *hierarchical planning* /14/[2] which is similar to the multi-layer control structure mentioned above. The planning of a sequence of *world situations* without (a detailed) conclusion on the actions is a special (but in the ATM-domain very useful and already practiced) variant of a vertical decomposed planning. In the subordinate layer

1) an area k may contain several intersections

2) This term is also used for a special architecture of the *distributed planning* of the TARMAC planning system where several, single-aircraft planners are coordinated by a superior planning unit).

of such a *situation planning* the experiences of the human-operator can be used for the determination of an appropriate sequence of actions (control instructions for the pilots) to achieve the desired *situations*.

2) The characteristic of the second option is the reduction of the developmental possibilities through reduction or limitation of the *planning horizon*. This can be done either by generation of sub-goals, the execution of which guarantees or facilitates the satisfaction of the original goal, or by fixing of a certain limited *horizon* (*incremental planning*) /15/. If planning of future traffic handling is still done by the controller and only supported by a *planning support system* there is in addition the possibility that the *horizon* can also be chosen by the controller according to the available time for the planning process or according to his assessment of the final planned traffic situation.

4.3 Human-Machine Interaction

The problem of human-machine interaction is often reduced to the problem of human-machine interface design to answer the question how the human-operators can work with the system. Of course, the layout of the interface is very important for the human-operators' acceptance, because it has a direct effect on their workload. However, in the context of *automatic planning*[1)] there are many other questions which have to be answered long before even a prototype of an interface can be made. These answers react upon the implemented planning algorithms and the used planning methods.

So, how does a *reactive planning*, the plans of which are made for a human-operator, differ from others which are made to control machines, e.g. robots? Focussing our attention on planning for humans, especially for controllers, the main differences are:

- ☐ There is a general guideline that the controllers retain the authority in such a human-machine system as well as they should keep the responsibility for traffic handling. Both points presuppose a possibility to influence the planning system.
- ☐ For the controllers it should be possible to realize the plans without an increasing workload, therefore:
  - ☐ *Single-plans* must not be changed as often as it might be desirable to achieve the planning goal in an optimal way (shortest time, least expense, etc.).
  - ☐ If it is unavoidable to change a *single-plan* it should be done in such a way that the new plan is "similar" to the old one. This problem is called the *plan stabilization problem*.

1) It is important to keep in mind that the human-machine interaction is only pointed out for the case that there is an **automatic** planning system, not an interactive one.

The general problem of the role of a human-operator in a human-machine system should not be discussed in this paper /16/. However, if only the technical side is discussed, the question remains how a controller could influence an automatic planning system. Two ways of the controllers influence on an automatic planning system should be distinguished: the *direct* and the *indirect influence*.

The *direct influence* is characterized by the controller modifying or replacing a calculated plan by his own one. An often discussed example is the ability of the controller to assign a new (in his mind better) taxi-path to an aircraft. But, as already pointed out, the plan of the controller is needed for *plan monitoring* and for further planning. Therefore the controller has to "inform" the planning system about his plan. Although there are modern communication methods (window surfaces, voice recognition etc.), which enable him to do this with little effort, a crucial problem is hidden - the difference between the controllers and the machines *world model*. There might be cases where only the planning system detects a *planning conflict*. Then the planning system would have to ask the controller how he would solve it (e.g. the future right of way order for the aircraft at a certain junction). Depending on the answer of the controller, the planning system can have the "impression" that plans of other aircraft have to be modified according to the controller's intention. So in certain cases, either a very complicated time consuming human-machine dialog has to take place or further planning has to be done under the uncertainty of an old *single-plan* that unavoidably leads to a loss of optimality.

If the controller has mainly the possibility to change planning conditions, constraints or the optimization criterion for traffic handling in the near future according to his intentions, he has an *indirect influence* on the planning process. Of course a translation layer as part of the intelligent HMI is needed which enables the controller to do this without any knowledge about the details of the planning algorithm. Examples on how influence can be exercised, are:

- ☐ the aircraft should not stop at certain locations,
- ☐ the plans should change less frequently, and
- ☐ a certain aircraft should have the highest priority.

The advantages in contrast to the *direct influence* are, that

- ☐ there is no time consuming dialog needed,
- ☐ the planning system has full information about all plans (consistency of information), and
- ☐ the controller is able to put influence on all future planning according to his intentions.

It should be mentioned that there are many additional difficult problems in the design of the HMI which are closely related to the planning algorithms, for instance, the timely display of planned actions (*plan translation problem*), and the determination whether (and if so, what) actions are necessary to reach the (next) planned

situation[1)] (this is part of the *plan transformation problem*). But, since they do not feed-back to the design of planning algorithms they are not described here in more detail.

Now the second point is again considered, namely: what has to be done to enable the controller to realize the plans without an increasing workload. To guarantee that the plans do not change very frequently a plan with a sufficient prevention against the uncertainty is needed. For *plan stabilization* information of an old plan must be used for planning. Therefore it is expedient to introduce three types of planning:

- ☐ *new planning* or *repeated planning* without any information of an old plan (e.g. for new incoming aircraft),
- ☐ *replanning*, which means planning under consideration of old plan information either for constraints or for the measure of the similarity between a currently computed and the old plan (e.g. the planning of taxi operations on a former planned taxi path for an aircraft),
- ☐ *plan modification* in which only one item (e.g. the push-back time) of a *single-plan* is adapted.

In general the last two planning types are not only useful to change plans smoothly, but also to reduce the computation time for a plan.

5 Example: Runway Occupancy Planning for Departures

5.1 Problem Description

5.1.1 Objectives of Occupancy Planning

Although "capacity of an airport" is a commonly used term in the domain of Air Traffic Management (ATM), its exact definition is still disputable. The main reason for that seems to be the dependence of the capacity on various "environmental" factors, such as weather situation (wind, visibility) and traffic mix. Of course, capacity is primarily based on the runway system and the prevailing operational procedures, like the runway configuration. Many of these factors cannot be measured quantitatively but can only be described qualitatively. Furthermore some factors vary in time, thus capacity is time-variable, too /17/.

However, it is clear: airport capacity limits the number of movements and in case traffic demand exceeds capacity for a certain time (arrival peaks) the delays of the arriving aircraft grow. Therefore in practice, capacity is often regarded as the maximum throughput or its definition can be based on the throughput at which the average delay does not exceed a certain amount /11/. Since arrivals have to be served with priority, departing aircraft often do not reach their scheduled times, too. But the present operational procedures force a surprising interdependence between delays and capacity: On the one hand airport overloading "produces" delays, but on the other hand certain departure delays are necessary to reach maximum capacity in case the same runway is used for arrivals as well as for departures. This can be explained as follows: In order to fill any gap in the arrival stream with departures the controller, who has no complete information about future events, about the current traffic situation on the apron etc., needs a queue of departures waiting (with running engines!) at the departure runway to react (skilfully!) so that at least no constraints which are critical for the safety are violated.

Thus the main objective for an occupancy planning system is the enhancement of airport capacity by reducing the average departure delay. Moreover runway occupancy planning shall help

- ☐ to deliver the departures on time or within desired time intervals (slots)
- ☐ to coordinate the ground handling procedures of the airlines, the apron activities, especially the push-back sequences, and the superior departure planning

and in the farther future

- ☐ to coordinate arrival and departure management
- ☐ to generate planning goals for other planning subsystems of a SMGCS /TARMAC.

5.1.2 Present Operational Procedure (OP)

Before an aircraft is able to depart, several activities are necessary which are done under the responsibility of four institutions: the airline itself, Apron Control, Tower Control, and Air Traffic Control (ATC).

The duration of the airlines' ground handling procedures determines the earliest time the aircraft could leave its parking position. The experience and knowledge of the pilots, their familiarity with the operational procedures of the airport and their own intentions lead to great variations of the times needed for push-back and taxiing.

Apron Control done by several apron controllers manages the traffic on the apron(s) of an airport. That means for departures: to schedule their push-back operations, to determine their taxi paths from gate to the movement area, and to give right of way instructions to the pilots.

Tower Control done by a controller named PL is responsible for taxi guidance, for runway management (line-up and take-off clearances), and to maintain defined separations between aircraft on the standard (instrument) departures routes (SID) aircraft fly after take-off.

ATC integrates the aircraft into the air traffic flow under consideration of superior aspects of the *Air Traffic Management* (ATM).

[1)] In this context only plans were considered, which do not contain a sequence of actions but a sequence of desired situations.

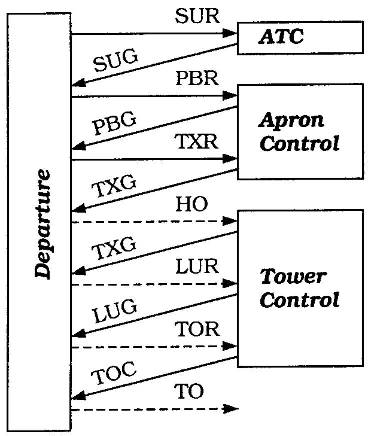

Fig. 4. Present operational procedures from start-up request to take-off

Dotted lines: observed events.

Abbreviations: SUR = Start-Up Request, SUG = Start-Up Given, PBR = Push-Back Request, PBG = Push-Back Given, TXR = Taxi Request; TXG = Taxi (Clearance) Given, HO = Hand-Over; LUR = Line-Up Readiness; LUG = Line-Up Given; TOR = Take-Off Readiness; TOC = Take-Off Clearance; TO = Take-Off

Today activities for a take-off are initiated by a pilot (see fig. 4). He requests a *Start-Up* from ATC. Expecting that the aircraft will need a certain time to reach the runway and under consideration of ATM aspects, permission for *Start-Up* is given. Then the pilot requests the permission for *Push-Back* operation (and *Spool-Up* of the engines) from the Apron Control. The apron controller tries both to hand-over the aircraft in due time to the Tower Control and to coordinate the push-back and the taxi operation of this aircraft with all activities necessary for other aircraft. Under this consideration push-back and taxi instructions are given to the pilot. After hand-over suitable instructions for taxiing, line-up, and take-off have to be given from the PL to meet all constraints mentioned above.

5.1.3 Given and Generated Information

Human planning as well as Automatic Planning has to be based on relevant information that is obtainable (measurable, observable) from the system for which planning should be done, called *world*. In order to reduce the quantity of information to a manageable amount, a certain level of abstraction is used which describes the *state of the world* through the sets of *Events* (***E***), of known arrivals ***A*** and departures ***D***, *Constraints* (***C***), and the *previous Plan* (***P***).

An *event* $\mathbf{e} \in \boldsymbol{E}$ can be:

- ☐ a departing aircraft starting a new step of its OP (SUR, SUG, PBR, ..., TO; see fig. 4)
- ☐ the announcement of a new (up to the present time t_0 unknown) aircraft
- ☐ a changed prediction for the touch-down time of an arrival
- ☐ the actual touch-down time of an arrival
- ☐ an alteration of other time constraints for the present or the future

Any planning has to take into account the following constraints:

- ☐ Wake vortex separations between two arriving or departing aircraft in dependence on their weight classes; stored in form of matrices ***W***.
- ☐ SID separations between all navigation aids (see fig. 5). The separation between two departing aircraft $\boldsymbol{R_{DD}}$ is than the minimum separation of the common flight path.
- ☐ Departures slots $\boldsymbol{S_D}$
- ☐ Minimum runway allocation times for the known arrivals $\boldsymbol{Y_a}$ and departures $\boldsymbol{Y_d}$
- ☐ Minimum sum times for all future steps of the OP $\boldsymbol{O_D}$ for every departure from ***D***.
- ☐ Some constraints resulting from the interdependence between the runway 18 and the runway system 25/07 that will not be explained in detail.

For the computation of $\boldsymbol{O_D}$ a model ***M*** of the OP is needed, which is a set of tables containing average times for steps of the OP (e.g. push-back and taxi times) distinguished both for different areas or gates of the apron and aircraft weight classes (heavy, medium, light) or types (B747, A320, etc.). Since some constraints result from the *events* they change with time.

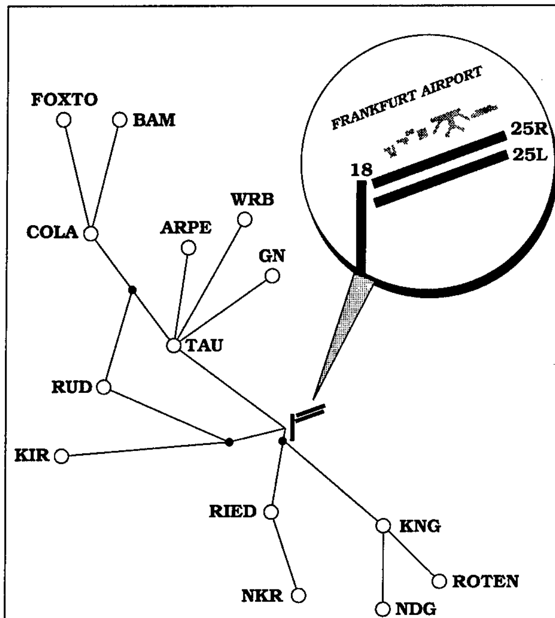

Fig. 5. (Simplified) Structure of the Standard Instrument Departure Routes from 25L+25R of the Frankfurt Airport

Navigation aids: FOXTO, RAM, WRB, ...,NDG, e.g. WRB=Warburg

It should be remarked that there are two kinds of constraints: the "strong" constraints that are safety critical and must not be violated in any case (wake vortex separations, minimum runway allocation times),

and the "weak" ones that can be violated "slightly", for instance in cases where no other solutions exist.

When considering plans it is useful to distinguish between primary plans $\boldsymbol{P}$ for runway allocation and derivative plans $\boldsymbol{p}=p(\boldsymbol{M},\boldsymbol{P})$ which correspond to the departures from $\boldsymbol{D}$. Any $\boldsymbol{p}$ contains latest times for the SUG, PBG, TXG, HO, and LUR of the OP of the respective aircraft.

5.2 Functional Structure of the Planning System

5.2.1 Superior Runway Allocation

Considering the specific runway configuration of the Frankfurt Airport the planning system was subdivided into a Coordinator Unit and two planning units: for the runway 18 and for the parallel runway system (fig. 5). The coordinator allocates the departures to a certain unit using a set of allocation rules. Beyond that it has to do some other tasks in connection with the planning algorithms of each unit (see following text).

5.2.2 Functional Structure of a Planning Unit

Each planning unit calculates a primary plan $\boldsymbol{P}$ for a set of departures $\boldsymbol{D}$ containing all departures which were allocated to the corresponding runway. This process is triggered by the coordinator after the occurrence of an initial event at time t_0. So planning has to consider the actual constraints $\boldsymbol{C}(t_0)$. However, there is no guarantee that under these constraints a permitted plan really exists. As it is necessary for ATM to modify a certain constraint, like a departure slot, immediately in such a case, planning is done by two subunits:

- □ Sequencer: determination of permitted departure sequences
- □ Optimization Unit: optimization of occupancy intervals

5.2.3 Sequencer

The sequencer determines such sequences s_j of aircraft for which permitted occupancy intervals for the departures exist.

The allocation of a corresponding set of occupancy intervals (a preliminary plan $\boldsymbol{P}_p(s_j,\boldsymbol{R})$) is done by using a set of rules $\boldsymbol{R}$. When applying $\boldsymbol{R}$, it has not only to be guaranteed that a $\boldsymbol{P}_p(s_j,\boldsymbol{R})$ will be found for any s_j but, since in case that decisions are urgently required, the plans p for certain departures have to be derived immediately from the $\boldsymbol{P}_p$, the above mentioned aspects of plan stability and uncertainty have to be considered.

As in general a large set of permitted sequences exist and also in order to cut the search tree, an evaluation criterion $f(s)$ is used to select an subset of "sensible" sequences.

5.2.4 Optimization Unit

The Optimization Unit does not only consider whether a plan is permitted, but moreover other aspects such as:

- □ similarity to the previous plan
- □ robustness against uncertainty
- □ priority of aircraft
- □ violation of (weak) constraints.

Therefore an optimization function

$$g(\mathrm{C}(t), \mathbf{v}) = \sum_i \alpha_i g_i(\mathrm{C}(t), \mathbf{v}), \quad \sum_i \alpha_i = 1$$

is used where each g_i measures a certain aspect depending on the $2n_D$ boundaries of the occupancy intervals that are stored in $\mathbf{v}$, and α_i is a weight factor.

Since in general there are a lot of (local) optimal solutions which minimize g, an advanced optimization technique is used which is able to find the global (or a sufficient) optimum.

Every optimization process starts with the population of the previous planning, but with a changed evaluation of all individuals. During the planning process new individuals representing permitted solutions and generated by the sequencer are added consecutively to the population. At any time the best solution found so far is accessible from the database. The coordinator decides by consideration of the available push-back preparation times whether for a departure j the plan $p_j \epsilon \boldsymbol{p}$ has to be fixed (fig. 6). Then the optimization is continued with a set start time of the occupancy interval j.

5.2.5 Coordinator Tasks

Beside the allocation task the Coordinator Unit controls not only the planing processes in the planning units but also serves as an interface to the *world* (via other ATC systems) as well as to the controller displays. The Coordinator Unit

- □ updates the *event list* $\boldsymbol{E}$ and constraints $\boldsymbol{C}(\boldsymbol{E})$
- □ proves whether a new *event* requires a new planning
- □ derives the plans $\boldsymbol{p}$ from $\boldsymbol{P}$
- □ initiates the modifications of constraints in case no permitted $\boldsymbol{P}$ exists
- □ establishes priorities to those aircraft of which push-back is in preparation or already done, to avoid delays caused by changed plans

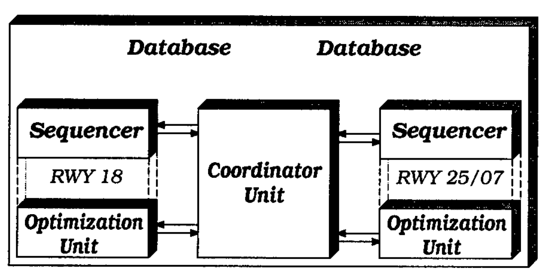

Fig. 6. Functional Structure of the Occupancy Planning System

5.3 System Development and Evaluation

As explained in previous chapters occupancy planning requires a complex interaction of several subsystems. The influence of the implemented algorithms (sequencing, optimization etc.), of the several parameters and of the optimization criteria on the departure delays, resulting from the plans of an event-driven recurrent planning, is not obvious and there is no theoretical method known to quantify this influence in advance. Moreover, the evaluation of a certain realization of the planning system cannot be restricted to average departure delays because the frequency and the amount of violations of weak constraints, or the number of slots which might have to be rearranged, are important aspects, too.

Besides these technical aspects, the operational side has to be evaluated. So questions like, e.g.: what information should be displayed at which time (relating to a certain event time) in which way, have to be answered. This should be done as early as possible because this does not only has an influence on controllers' workload but a backward effect on the design of the planning algorithms.

The interdependence between planning algorithms and working procedures of the controllers can be investigated in the best way, by using a simulation system that is integrable into a realistic simulation environment including a tower mock-up which is already available at DLR. The simulation system which is currently under development generates all *events* based on realistic scenarios of arrival traffic and departure flight plans.

The workload of the controllers that is very important for their acceptance is moreover affected by plan stability. In order to decide whether (a certain realization of) the occupancy planning is able to generate "stable" plans a time-variable space of tolerable variation will be defined.

6 Conclusions

The management and control of complex systems by human operators can be improved considerably if they are assisted by an automated planner that considers all available information about future constraints, goals, events etc. as well as the present state of the system. Since in general the behavior of the *world* is not predictable with arbitrary accuracy a dynamic planning has to be designed that is characterized by information feedback and a permanently working situation assessment.

Depending on the characteristics of a given domain, influencing factors like e.g. : planning with uncertainty, situation assessment in real-time, planning with time-intervals and recurrent planning with sliding horizon have to be considered in the design and development of intelligent planning systems. If furthermore human operators have to interact with the planning support system, which is typical for the ATM domain, special provisions have to be designed from the beginning into the planning algorithm.

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ATFM: Optimisation Approaches

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Abstract
European centralised air traffic flow management (ATFM) is still in its early stages of development and has urgent and extensive needs in terms of decision support tools. This paper provides a brief overview of research in ATFM and discusses the feasibility of optimisation approaches to European ATFM. Three optimisation models for re-routing air traffic flows and their test results are presented and analysed.

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1. Introduction

Congestion in the air transportation system has been plaguing air traffic both in the US and in Europe for nearly 20 years. In order, to protect air traffic control (ATC) from overloads, a planning activity called air traffic flow management (ATFM) emerged during the seventies. ATFM, by comparing the available capacity with forecast traffic demand sometime prior to the flights, tries to anticipate overloads and take control actions to prevent them. In simple terms, the capacity of an ATC sector is defined as the number of flights that the air traffic control team of that sector is able to supervise per period of time, usually one hour. When the traffic expected to cross the sector exceeds the capacity, traffic delays occur. In [8] it is claimed that delays caused by lack of capacity cost European carriers around $3 billion annually. ATFM tries to limit the extent and impact of those delays.

ATFM control actions range from departure delays to re-routing of flights. Departure delay, or ground-delay, means delaying departures of flights heading to congested areas. The idea behind it is that, if delays are unavoidable, it is safer and cheaper to delay the flights on the ground than in the air. Flights can be re-routed to by-pass already overloaded elements of the airspace or to prevent overloads occurring.

In continental US there is a single body located in Washington DC which co-ordinates flow management: the Air Traffic Control System Command Center. Congestion problems in the US are experienced mostly at airports. In Europe, a continent with many countries each with its own airspace, co-ordinated air traffic control and flow management is more difficult to implement. As stressed by Benoît [6] many flights in Europe take only one hour or less but have to cross several airspaces. Congestion is felt not only at airports, as is mostly the case in the US, but also in the airspace at the junction points of air routes (also called fixes). Therefore, the thrust of air traffic management and control efforts in Europe has been to integrate and centralise control activities. To this end, the Central Flow Management Unit (CFMU), located in Brussels, was created in 1989 to be the sole provider of air traffic flow management in the 33 countries of the European Civil Aviation Conference.

Matos and Ormerod in a paper based on fieldwork done at the CFMU in 1995 [13] address the differences in timescale and organisation of ATFM activities between the US and Europe: in the US most of the planning is done a few hours before the flights depart by the Air Traffic Control System Command Center whereas in Europe the planning starts six months before the flights and involves not only flow managers but also different National Administrations, area control centres (ACC) and aircraft operators' representatives. Accordingly, concepts differ: US authors tend to call all the planning done before the flights

take-off "Strategic" and after the flights take-off "Tactical". In Europe, there is Strategic planning which goes from 6 months ahead to a few days before the flights, Pre-tactical planning which occurs on the two days before the flights and Tactical planning which takes place on the day of the flights until take-off. Measures affecting airborne flights are considered strictly in the realm of ATC rather than ATFM.

These three levels of planning differ in the timeframe considered, the uncertainty involved and the room for manoeuvre. At the strategic level, where the control measures are prepared a few months beforehand to last for a whole Summer season, there is scope for significant changes in the routing of flows. However, the information available on traffic demand a few months ahead is very uncertain. As the day of operations gets closer the information available becomes more accurate but the room for introducing changes diminishes. The distinction between the different levels of planning can also be blurred, for instance, when control measures are prepared a few weeks before the flights.

Research on ATFM problems started in the late eighties: Odoni in [15,16] defined the air traffic flow management problem area, identified major issues in the field, and suggested the decision support needs, mostly based on the US situation. In [13] some ground-clearing work is done for European ATFM. Most of the ATFM research has concentrated on optimisation models for the allocation of ground-delays with nearly all models intended for the US case, with congestion limited to airports [1,2,3,4,16,18,19,22,26,27]. Recently, research has been reported on ground-delay models where congestion also affects sectors en-route [7,11,23,24,25]. Examples of the application of simulation to ATFM have also been reported [30]. There has been some work published exploring the application of artificial intelligence techniques to ATFM [5,9,10,17,20,21,29]. Research on decision support models and systems for re-routing of flights is just starting: in [14] a re-routing demonstrator and optimisation models for the re-routing of air traffic flows are presented. In [23] an integer programming model that allocates both ground-delays and routes to individual flights is described. A research project aimed at developing decision support aids for re-routing of flights, Computer Aided Route Allocation Tools (CARAT), started in May 1995, at the Experimental Centre of Eurocontrol [12]. This project is exploring the use of meta-heuristics such as Simulated Annealing, Tabu Search and Genetic algorithms to re-routing problems.

This paper looks at the feasibility and of optimisation approaches to European ATFM. In so doing, optimisation models intended for pre-tactical re-routings, that is routings of air traffic flows, issued a few days before the flights take place, are presented.

2. Feasibility of Optimisation Approaches

Optimisation of the flow of air traffic is the second priority of ATFM, the first priority being to ensure the safety of air traffic. Defining and implementing optimisation of the air traffic flow is a complex problem: there are many different traffic flows interfering with each other and optimisation has different meanings to the different users of the airspace. These meanings can also vary dynamically. For instance, charter airlines tend to give priority to the minimisation of the operational cost of flights, whereas scheduled airlines tend to give priority to the minimisation of flight delays but, these priorities may change: a charter airline on a certain day, to make sure that an aircraft is available at a certain airport for another flight will give priority to the minimisation of the delay of a flight going to that airport.

European flow managers will typically use traffic loads and total delay as the main criteria to optimise the flow of air traffic and in order to ensure equity, flights are ordered by time of filing the flight plans or expected arrival time. The efficacy and degree of optimisation relies on the co-operation of the different stakeholders For example, if, at tactical level, delays are building up flow managers may try various control measures to reduce the delays: 1) to increase, in co-ordination with the Air Traffic Control Centre concerned, the number of flights that can cross the sector that is causing the delays 2) to convince some of the airlines whose flights have acceptable alternative routes to re-route thus by-passing the congested sector.

There are clearly two very distinct levels of optimisation: The optimisation done dynamically in a real environment that results from the influences exerted by the various stakeholders (airlines, ATC, flow managers etc.) and the optimisation defined in a mathematical model. The mathematical model provides consistency, quantitative information and speed to the decision process but it cannot take into account all the dynamic and non-mechanistic decision criteria that guide the optimisation in a real ATFM environment. Considering that ATFM is a largely human centered activity with many different and sometimes conflicting stakeholders, optimisation models for ATFM have to be designed more as decision aids than as decision makers.

Therefore, in the development of optimisation models for ATFM (and for any other human activity) the following questions have to be answered beforehand: Why are they used, who uses them, where and when are they used. In other words, the feasibility of optimisation models relies on an adequate knowledge of the users, their decision support needs and the context in which the models are used. Other key more technical factors in the feasibility of optimisation models are their efficiency, defined in terms of execution time and size, and how easy it is to integrate them in a decision support system (e.g., the amount of data processing needed).

The acceptance of optimisation models by the user and other stakeholders is a key factor in their success. Andreatta *et.al.* [3] stress that in many circumstances optimisation models are seen as a "black box" and the users do not trust them, preferring the use of more transparent heuristics. Ward [28] in an article providing arguments for the use of simple models recognises the importance of client involvement and acceptance of the models. At the CFMU, the algorithm in use for the allocation of ground-delays is based on a FIFO heuristic, a heuristic which has been used in practice for a while and that flow managers and airlines trust more.

In many decision-making processes optimisation models have to be coupled with other types of approaches. Odoni [16] considers three types of approaches to address ATFM problems: 1) Manual solutions 2) Knowledge-based expert systems 3) Exact and heuristic algorithms. Winer [30] describes computer tools where optimisation approaches are coupled with simulation.

In the following sections optimisation models for the re-routing of air traffic flows are introduced taking into account the feasibility aspects mentioned in this section.

3. Optimisation Models For Re-routing Air Traffic Flows

3.1 Modelling Approaches

A key issue in determining the effectiveness of re-routing measures discussed in [13] is the degree of authority that flow managers at the CFMU can exercise. At present, only some of the routings at the strategic level, or those in contingencies or in severely congested situations are mandatory. All other re-routings tend to be advisory. Mandatory re-routing measures apply to flows, during certain periods and are usually negotiated beforehand with airline representatives and the area control centres involved, they cannot be imposed on an individual flight basis. The choice of air route for a particular flight is seen as a commercial decision to be taken by the airline.

However, there is an on-going debate on the adequacy of the present situation, and whether there should be more or less regulation [13]. Some stakeholders in flow management argue in favour of a firmer regulatory control, where responsibility for the provision of flight plans, including the flight route, lies with ATFM. In this case, airlines just file the airports of departure and destination, type of aircraft, number of passengers and state their preferences.

The nascent research on optimisation models for re-routing measures [12,23] assumes that flow management do have the authority to route individual flights. The modelling approach taken in CARAT [12] works at the level of the individual flight: the European airspace is represented as a network model and the objective of the model is to minimise the sum of

operational routing costs and of congestion costs. Congestion is measured by means of demand/capacity imbalances. The input to the model is the initial flight plans, and the output is the flight plans resulting from the optimisation. This approach will work if flow management has the authority to change flight plans and if efficient algorithms are developed to solve the very large optimisation models resulting from it.

In practice, at present, flow managers, when considering pre-tactical re-routing measures, group flights into main flows, according to origin destination areas. They then identify alternative routes for the flows and compare capacity with demand for ATC sectors, in an iterative way. The alternative routes have to be acceptable to airlines, that is, they cannot be too long or too costly. The modelling approach taken in this paper is based on this practice and assumes that flow managers have authority to issue re-routing measures applying to whole flows during a very well defined period, typically a day. Routes cannot be changed frequently nor be allocated on an individual flight basis.

Flights are grouped into flows according to their origin-destination, and the problem of re-routing air traffic flows is solved in two stages: 1) **Routes Problem:** identify acceptable and alternative routes for each flow; 2) **Assignment Problem:** given a set of flows, a set of acceptable routes and a set of capacity constrained sectors, assign a route to each flow so that the total cost of re-routings and congestion is minimised. This approach results in smaller, easier to solve models but is less direct than the approach used in CARAT, as before reaching the optimisation phase flights have to be grouped into flows using simplifying criteria. However, it should be noted that if the flow variables are replaced by flight variables the models here presented can also be formulated in terms of individual flights.

3.2 Formulations and Size

When modelling the above mentioned assignment problem, there is the question of how to represent congestion. At least, two possibilities can be considered: (1) Use penalties whenever traffic demand exceeds the capacity of an ATC sector. (2) Use ground-delays to keep the demand within the capacity. Possibility (2) is justified by the fact that congestion results in ground-delays, but it can lead to large-size integer problems. It should be stressed that at this level of planning, ground-delays are in the problem just to support the decision on the re-routing of flows. The actual allocation of ground-delays will be done by the CFMU computer system, TACT, on the day of the flights. Possibility (1) reduces substantially the size of the problems, but because it does not take into account the cumulative effect of capacity/demand imbalances over time it may underestimate congestion. Both possibilities are explored in this paper.

Models with ground-delays have two types of decision variables: (1) Variables assigning one route to each flow. (2) Variables assigning ground-delays (or departure time periods) to flights. The first type of variables depends on the number of flows and the choice of routes available. The definition of the ground-delay variables, given the large number of flights involved, is not immediate. If a binary variable is defined for each flight in a flow, on each route and time period, the number of variables easily reaches 100 000. This is an unmanageable number of variables for an integer programming model. For instance, if the following decision variables are defined:

$$y_{ijzt} = \begin{cases} 1 & \text{if flight } z \text{ of flow } i \text{ is delayed on route } j \text{ at } t \\ 0 & \text{otherwise} \end{cases}$$

and considering a scenario, say, just including part of the French airspace, of 20 flows with 60 flights and 2 alternative routes each, and a period composed of 50 time intervals the number of ground-delay variables totals 120 000.

Another possibility is to model ground-delay variables in terms of 'number of flights delayed". For example, considering the following variables:

d_{ijt} number of flights of flow i departing on route j at t

y_{it} number of flights of flow i ground - delayed at t

the number of variables for the above scenario is reduced from 120 000 to 3 000. A drawback of this approach is that the length of delays affecting the flights is not taken into account.

To overcome this drawback, variables can be defined in a more detailed way (this formulation draws on a ground-delay model presented in [25]:

$d_{ijtt'}$ number of flights of flow i, on route j that are scheduled to depart at t and are departing at t'

For the above scenario, this formulation results in 51 000 variables, a large number, but still, substantially smaller than the formulation with binary variables. The models with ground-delays that are now described are based on the two last sets of variables discussed above.

3.3 Models

The models now described are intended for the assignment problem defined in section 2. They assign a route to each traffic flow in order to minimise the cost of congestion and re-routings. Three integer programming models resulting from different ways of measuring congestion are presented (see mathematical formulation of the models in the appendix):

BALDIST- Congestion is measured by means of penalty variables that are activated whenever traffic demand is above the capacity of an ATC sector. The model minimises

the sum of the estimated cost of congestion and the cost of re-routings subject to capacity constraints and constraints on the assignment of routes to flows.

DELINT1- Congestion is measured using ground-delay variables of the type "number of flights of flow i delayed at t". The ground-delay variables are in the model to support the decision on re-routings, not to allocate ground-delays to individual flights Therefore, unlike BALDIST, flights ground-delayed can build up over time. The model minimises the sum of the estimated cost of ground-delay plus the cost of re-routings subject to capacity and assignment constraints plus constraints defining and relating the two types of variables: assignment and ground-delay variables.

DELINT2- Congestion is measured using more detailed ground-delay variables than in DELINT1: number of flights of flow i scheduled to depart at t and departing at t'. Therefore, this model takes into account not only the number of flights ground-delayed but also the number of time periods flights can be ground-delayed.

These models are based on the following assumptions:

1- All flights in a flow, that is flights with the same origin-destination, fly the same route, at the same speed. The limitations of this assumption are not serious because airlines tend to follow the same (cheapest) route and use the same type of aircraft for the same city-pairs. In addition, it should be noted that the time intervals considered are long and the models are not detailed to the point of providing exact times for individual flights.

2- The period of time for which flow re-routings are being considered is divided into p identical time intervals. These time intervals work as time units: the events 'Flight departure', 'Flight arrival', 'Flight Entry in Sector' are assumed to take place at the beginning of the corresponding time interval. Parameters like 'the time it takes to get to a certain sector on a certain route' are measured in 'number of time intervals'. If a flight crosses two sectors in the same time interval then the number of time intervals it takes to get to both sectors is the same and the crossing time for these sectors is 0 time intervals. This assumption is consistent with the way capacity of an air traffic control sector is defined for air traffic flow management purposes: 'number of flights per time interval'.

3.4 Testing the Models

The set of data used to test the models is based on the actual traffic crossing the French upper airspace on 25/04/96, from 03.00 to 22.00h, totalling 3582 flights. The French airspace was chosen because it is at the crossroads of the European airspace, with approximately 25%

of the whole ECAC traffic, and many of its sectors are often congested. The preparation of the data from the flight plans to a format able to run through the optimiser took approximately six months and can be broken down into four interrelated stages: identification of ATC sectors and capacities, identification of flows, determination of routes and sorting of the flights.

A flow is here defined as a set of flights departing from one airport or an airport area to another airport or airport area. The flows have a tree-like structure: many flows have very similar routes differing only in the *length* of the extremities, that is the first and/or last segments of the route. It should also be noted that the larger is the number of flows considered the larger is the possibility set for routing flows, thus increasing the flexibility of ATFM. The total flows identified for re-routing control measures is 138 corresponding to 920 flights.

The cost of the alternative routes is an estimate of the fuel cost incurred with the re-routing, by flying longer or at a lower altitude. To estimate the cost of congestion or ground-delay several possibilities were considered, three, one for each model are described below:

- BALDIST- $g_z = 400 \cdot z^2$ z is the number of flights above capacity
- DELINT1-

  $g(i,t) = a.(1 + m(t) / \max(1, f(i,t))$

  where

  a is a constant representing a basic cost of delay; the number used is a=147

  i is the flow index

  t is the timeperiod index

  $m(t)$ a constant that depends on the potential capacity - demand imbalances at t

  $f(i,t)$ flights of flow i scheduled to depart at t

- DELINT2-

  $g(t' - t) = a.(t' - t)^2$

  where

  a is a basic cost of ground - delay; the value considered initially is $a = 2500$

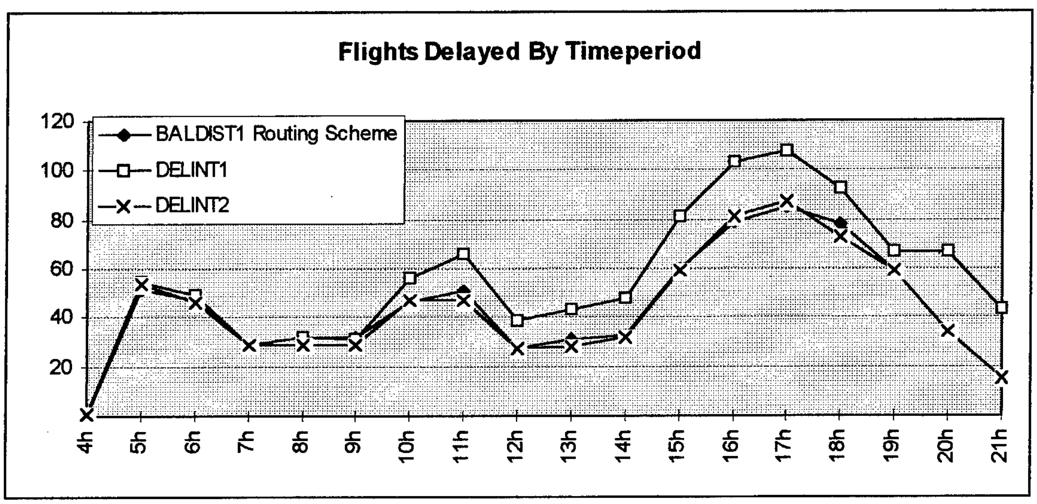
  t' departure timeperiod

  t timeperiod at which the flight was scheduled to depart. $t < t'$

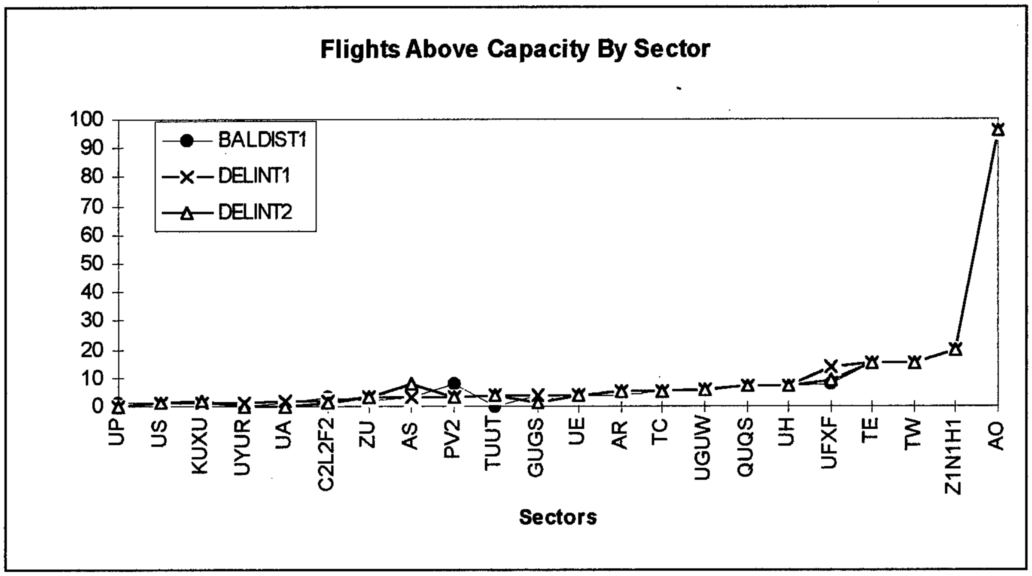
The period from 03.00h to 22.00h is divided into 19 hourly timeintervals with an additional 20th for DELINT1 and DELINT2 to allow delayed flights to depart. The models were solved using GAMS 2.25 modelling system coupled with a standard integer programming package LAMPS 1.66 on a SUN/SPARC workstation.

The test revealed that the optimisation models developed can be of use in re-routing flows and can provide significant savings in delays. In the cases studied, compared with a situation where all flights take the best route, re-routings reduced total ground-delay in about 60% and produced cost-savings (cost of congestion+cost of re-routings) between 42% and 90%. However, these results should be seen in context: they apply to an extreme situation where all flights take the best route irrespective of the congestion situation, in a real environment, some airlines and flow managers re-route flights to by-pass congested elements of the airspace.

Comparing the models, the test suggests that BALDIST, the simplest model, is the most efficient model of the three: It is considerably smaller than the other models (917 constraints and 303 decision variables compared with DELINT2 10854 constraints and 30919 variables), substantially faster (30 sec of execution time compared with DELINT2′ 5 minutes) and, despite not taking directly into account the building-up effect of congestion, it provides results almost as good as DELINT2 (see figures). DELINT1 in spite of being smaller than DELINT2 proved harder to solve to optimality and a feasible solution obtained in approximately 8 min of CPU, whose value is less than 0.8% far from the optimum value, was collected. DELINT2 offers the best results in alleviating congestion, and provides more information than the other models but it is a large model thus requiring much more space than DELINT1 and BALDIST and more time than BALDIST to be solved.



Note: For this comparison, as BALDIST does not provide flights delayed, DELINT2 was run using the routes obtained from BALDIST.



To assess the feasibility of the models several criteria can be considered: appropriateness of the support provided, flexibility and acceptance by the user (the flow manager), data requirements, size and execution time.

- **Support Provided:** It is important to recall that these models are intended for pre-tactical ATFM, a planning stage with a time horizon of a few days where traffic is analysed in aggregate terms, by flows instead of individual flights. Therefore, what flow managers need to know, when considering re-routing control measures, is which flows to re-route, onto which routes and the effect these re-routings will have on congestion, measured in ground-delay and/or capacity- demand imbalances. BALDIST provides routing schemes and their impact on capacity-demand imbalances, DELINT1 and DELINT2 in addition to that information, provide an estimate of delay by flow and timeperiod, with DELINT2 providing also the length of delay affecting flights.
- **Flexibility and Acceptance By the User**: To assess fully the flexibility and acceptance by the user the models have to be tested by the user, which has not be done yet. Some of the parameters of the models are easily changed: traffic demand, capacities, constraints on which flows to re-route, costs of delay and of re-routings, number of timeperiods considered. Other features, such as the definition of sectors, routes and flows are not easily changed. In an environment where patterns of traffic change daily, ATC sectors are split or merged daily in different but pre-defined configurations, this difficulty to change is a limitation.
- **Data Requirements:** The centralised systems in place at Eurocontrol provide updated traffic and airspace data, however prior to running the optimisation models several data processing operations have to take place: flows have to be defined, the

alternative routes for each flow determined and represented in terms of the sectors they cross and the traffic data grouped into flows and departure timeperiods. These operations require, either an experienced human user to define the relevant flows beforehand or a partly "intelligent" computer system able to define flows.

- **Size and Execution Time:** The execution time of the models is not as critical at pre-tactical as at tactical ATFM, however to be repeatedly and daily used by flow managers, the models have to provide solutions in relatively short timespans, say of 30 minutes maximum. Considering the impact on congestion, the execution time and the size, BALDIST appears to be the most efficient model of the three. The comparisons done show that BALDIST results in alleviating congestion both in terms of capacity-demand imbalances and ground-delay are almost the same as DELINT2.

Another key aspect in the feasibility of the models is whether they can be embedded in a re-routing decision support system. If a highly automated system is intended, optimisation models on their own cannot serve as a basis for a decision support tool which suggests whole routing schemes to improve congested situations. A tool of this type would have to comprise, at least, three subsystems:

1. **Definition of Scope**

A system which defines the boundaries and scope of the problem, addressing issues such as which areas of the airspace should be looked at and how to define and what the flows to be considered are.

This system would need knowledge based on experience, traffic data, possibly in the form of case-based reasoning or heuristics, to work.

2. **Data Processing**

A mainly procedural system which pre-processes the traffic data in terms of routes and timeintervals, in order to be able to run it through the optimisation system, and can also process the output of the optimisation system in order to make it more understandable to the user.

3. **Optimisation**

A system which, given the boundaries defined in 1, and the data processed in 2 will provide the best routing scheme, suggesting which flows to re-route onto which routes and at what cost.

The benefits of a tool of this complexity and level of automation, will have to be measured against the clearly substantial resources needed to develop it. It is also possible to consider, at least as an intermediate stage, a less automated system, where the flow manager

has a more active role in the definition of scope and in adjusting results, and the processing of data and optimisation are performed by the computer.

If a more interactive and less automated system is intended, another possibility would be to couple the optimisation models with a simulation tool. The flow manager could use the optimisation model to obtain routing schemes and the simulation tool to assess, in a more detailed way, the feasibility of the solutions proposed by the optimisation model or vice-versa: use the simulation tool to build different routing schemes and the optimisation model to assess the deviation from the optimum solution.

4. Conclusions

In this paper, the feasibility of optimisation approaches to European ATFM is discussed and two classes of factors influencing feasibility are identified: 1) knowledge of the context and the needs of the different stakeholders (flow managers, ATC and airlines) 2) technical feasibility of the models (execution time, size and data processing needed). Drawing on this analysis, the pre-feasibility of three optimisation models for re-routing air traffic flows is assessed.

Two main directions for future work can be identified: 1) The study and definition of the decision criteria to be used in ATFM optimisation. A related issue that also needs to be addressed is the definition and implementation of equity in ATFM. 2) The study of approaches integrating optimisation models with other techniques, namely simulation and artificial intelligence.

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APPENDIX

Mathematical Models

Notation:

i index for flows. $i = 1,\ldots,m$

n total number of flights

z index for the *zth* flight above capacity. $z = 1,\ldots, \bar{Z}$

$\bar{Z}$ maximum number of flights allowed to exceed capacity. $\bar{Z} \leq n$

N_i set of flights in flow i. $\sum_{i=1}^{m} |N_i| = n$

k index for sectors. $k = 1,\ldots,l$

R_i set of routes acceptable to flow i

j index for routes. $j \in (\bigcup_i R_i)$

each route is defined by a sequence of sectors $k, k', k'' \ldots$ and a corresponding sequence of entry times $t_{jk}, t_{jk'}, t_{jk''} \ldots$

L_k set of routes that cross sector k

t index for time interval. $t = 1,\ldots, p+1$

t_{jk} time intervals it takes to get from departure point to sector k on route j

τ_{jk} time intervals it takes to cross sector k on route j excluding the entry time interval

$\tau_{jk} = \max\{0, t_{jk'} - t_{jk}\}$ where k' is the sector just after sector k in route j

u_{kt} capacity of sector k during t

f_{it} number of flights of flow i scheduled to depart at t. $\sum_{t=1}^{p} f_{it} = |N_i|$ $(i = 1,\ldots,m)$

c_j additional cost of route j

g_{zk} marginal cost of the *zth* flight above capacity in sector k

g cost of ground - delay per time period

$g(t)$ cost of t time periods of ground - delay

c_0, α constants in ground - delay cost function

Variables:

$$x_{ij} = \begin{cases} 1 & \text{if flow } i \text{ is assigned to route } j \\ 0 & \text{Otherwise} \end{cases}$$

$$o_{ztk} = \begin{cases} 1 & \text{if there is a zth flight above capacity at } t \text{ in sector } k \\ 0 & \text{Otherwise} \end{cases}$$

y_{it} number of flights of flow i ground - delayed at t

d_{ijt} number of flights of flow i departing on route j at t

$d_{ijtt'}$ number of flights of flow i on route j that were scheduled to depart at t and will depart at t'

1. Model BALDIST

For this model, a third assumption is added to the ones explained above:

3- The cost of the n*th* flight exceeding the capacity of an air traffic control sector is bigger than the cost of the (n-1)*th* flight.

$$\min w = \sum_{i=1}^{m} \sum_{j \in R_i} \sum_{t=1}^{p} c_j f_{it} x_{ij} + \sum_{z=1}^{\overline{Z}} \sum_{t=1}^{p} \sum_{k=1}^{l} g_{zk} o_{ztk} \tag{1}$$

subject to

$$\sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} \sum_{r=0}^{\tau_{jk}} f_{i,t-t_{jk}-r+1} x_{ij} - \sum_{z=1}^{\overline{Z}} o_{ztk} \le u_{kt} \quad (k = 1,\ldots,l; t = 1,\ldots,p) \tag{2}$$

$$\sum_{j \in R_i} x_{ij} = 1 \quad (i = 1,\ldots,m) \tag{3}$$

$$x_{ij} \in \{0,1\} \quad (i = 1,\ldots,m; j \in \bigcup_i R_i) \tag{4}$$

$$o_{ztk} \in \{0,1\} \quad (z = 1,\ldots,\overline{Z}; t = 1,\ldots,p; k = 1,\ldots,l) \tag{5}$$

Remarks:

1. another set of constraints could be considered:

$o_{ztk} \le o_{(z-1),tk} \quad (z = 2,\ldots,\overline{Z}; t = 1,\ldots,p; k = 1,\ldots,l)$

however as

$g_{zk} > g_{(z-1),k} \quad (z = 2,\ldots,\overline{Z}; k = 1,\ldots,l)$

these constraints will always be observed.

2. Calculating the maximum difference between traffic demand and capacity,

a tighter bound for $\bar{Z}$ can be obtained

$$\bar{Z} \le \max_{(k,t)} \left\{ 0, \sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} \sum_{r=0}^{\tau_{jk}} f_{i,t-t_{jk}-r} - u_{kt} \right\}$$

The objective of the model, represented in (1), is to minimise the total cost of re-routings and congestion. (2) are the capacity constraints affecting each ATC sector at each time interval and (3) make sure that a flow is assigned to one and only one route.

2. Models with Ground-delays

For both the following models there is also an additional assumption:

3- the capacity of sectors in time period $p+1$, the time period just after the end of the period during which the re-routing measures apply, is infinite. In practice, this means that in the time-period after the end of the re-routing the difference between capacity and demand will be sufficiently large to allow the backlog of flights ground-delayed to depart.

2.1. Model DELINT1

$$\min\ w = \sum_{i=1}^{m} \sum_{j \in R_i} c_j |N_i| x_{ij} + \sum_{i=1}^{m} \sum_{t=1}^{p} g y_{it} \tag{6}$$

$$\sum_{i=1}^{m} \sum_{j \in (R_i \cap L_k)} \sum_{r=0}^{\tau_{jk}} d_{ij,t-t_{jk}-r+1} \le u_{kt} \qquad (k = 1,\dots,l; t = 1,\dots,p) \tag{7}$$

$$\sum_{j \in R_i} x_{ij} = 1 \qquad (i = 1,\dots,m) \tag{8}$$

$$\sum_{t=1}^{p+1} d_{ijt} \le |N_i| x_{ij} \qquad (i = 1,\dots m; j \in R_i) \tag{9}$$

$$\sum_{j \in R_i} d_{ijt} = f_{it} + y_{i,t-1} - y_{it} \qquad (i = 1,\dots,m; t = 1,\dots,p+1) \tag{10}$$

$$x_{ij} \in \{0,1\} \qquad (i = 1,\dots,m; j \in R_i) \tag{11}$$

$$y_{it} \ge 0 \text{ and integer} \qquad (i = 1,\dots,m; t = 1,\dots,p) \tag{12}$$

$y_{i0} = 0, y_{i,p+1} = 0 \qquad (i = 1,\ldots,m)$	**(13)**
$d_{ijt} \geq 0$ and integer $\qquad (i = 1,\ldots,m; j \in R_i; t = 1,\ldots,p+1)$	**(14)**

Remark: The above variables are not independent. For instance:

$$d_{ijt} = (f_{it} + y_{i,t-1} - y_{it})x_{ij}$$

The objective of the model, represented in (6), is to minimise the total cost incurred in the re-routings plus the aggregated cost of ground-delays. The unit cost of ground-delays is assumed to be constant. (7) make sure that all the flights present in a sector at a certain time period do not exceed the capacity of that sector. (8) are the same as (3) and (9) ensure that flights do not depart on routes that have not been assigned to their flow. Finally, (10) state that the total flights of a flow departing at a time period t equal the total flights of that flow scheduled to depart at t plus the flights ground-delayed at $(t-1)$ minus the flights to be ground-delayed at t.

2.2 Model DELINT2

$$\min w = \sum_{i=1}^{m}\sum_{j\in R_i} c_j |N_i| x_{ij} + \sum_{i=1}^{m}\sum_{j\in R_i}\sum_{t=1}^{p}\sum_{t'=t+1}^{p+1} g(t'-t)d_{ijtt'} \qquad \textbf{(15)}$$

$$\sum_{i=1}^{m}\sum_{j\in(R_i\cap L_k)}\sum_{r=0}^{\tau_{jk}}\sum_{t=1}^{t'-t_{jk}-r+1} d_{ijt,t'-t_{jk}-r+1} \leq u_{kt'} \qquad (k = 1,\ldots,l; t' = 1,\ldots,p) \qquad \textbf{(16)}$$

$$\sum_{j\in R_i} x_{ij} = 1 \qquad (i = 1,\ldots,m) \qquad \textbf{(17)}$$

$$\sum_{t'=t+1}^{p+1}\sum_{t=1}^{t'} d_{ijtt'} \leq |N_i| x_{ij} \qquad (i = 1,\ldots,m; j \in R_i) \qquad \textbf{(18)}$$

$$\sum_{j\in R_i}\sum_{t'=t+1}^{p+1} d_{ijtt'} = f_{it} \qquad (i = 1,\ldots,m; t = 1,\ldots,p) \qquad (19)$$

$$x_{ij} \in \{0,1\} \qquad (i = 1,\ldots,m; j \in R_i) \qquad \textbf{(20)}$$

$$d_{ijtt'} \geq 0 \text{ and integer} \qquad (i = 1,\ldots,m; j \in R_i; t = 1,\ldots,p; t' = t,\ldots,p+1) \qquad \textbf{(21)}$$

The objective of the model is, again, to minimise the cost incurred in the re-routings and the estimated cost of ground-delays but taking into account the length of delays. (16) and (17), as in the previous model, are, respectively, the capacity constraints on ATC sectors and the constraints on the assignment of routes to flows. (18) ensure that no flights depart on routes their flows do not fly and (19) ensure that the number of flights departing equals the number of flights scheduled.

Conduct of the Aircraft: Flight Dynamics

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Abstract

Safety, production and operation costs have an influence on the design of aircraft flight controllers and ,thus, as well on the necessary sensors and actuators. Reliability and safety have a dominating role in this design process. Taking these premises into consideration, this paper describes some important aircraft flight control design aspects.

1. Introduction

Aircraft are potentially dangerous technical systems. High velocity during take-off and landing (during the transition from a ground vehicle to an aircraft) is associated with many dangers. Additionally, an aircraft, as opposed to a ground vehicle, has only a reduced number of possibilities for the correction of errors. For example, an aircraft can not simply be parked if the engine fails while airborne. Air accidents are often serious and, as a result, of interest to the media. The effect of the media is to make the risk of accidents appear higher. In spite of these principally unfavorable conditions, aircraft are presently one of the safest means of transportation. The probability of a fatal accident during travel by train or by airplane is about the same (Figure 1) when calculated on the basis of the distance traveled. In contrast, the risk of fatality in an automobile is ten times higher. The average number of fatal accidents per kilometer traveled at a typical traveling speed of 500 km/h is given in Figure 2 and is also given per flight hour in Figure 3 for the period of time between 1962 and 1980.

A clear tendency towards a decline in the safety risk from year to year can be seen. The risk of accidents has decreased by more than half during the two decades shown. In spite of this distinct trend, there are periods, such as during 1972, when there are an especially high number of accidents, or during 1976, when there were especially few accidents. There is usually no plausible explanation for such deviations from the trend. Figures 2 and 3 expose a further problem; namely, the unimaginable numerical values. Using the example of the trend values for 1976, an attempt shall be made to express these numbers in a comprehensible manner. The number of fatal accidents is at $3 \cdot 10^{-9}$ per kilometer, respectively at $2 \cdot 10^{-6}$ per hour. However, the reciprocal values appear to be easier to imagine. $3 \cdot 10^{-9}$ fatal accidents per kilometer correspond to accident-free flight of 300 million kilometers or circling the globe 7000 times. At an accident rate of $2 \cdot 10^{-6}$ per hour, a passenger would fall prey to the fate of a fatal accident after an average of 500,000 hours or 57 years of flight time. These values are within the bounds of normal risk to life.

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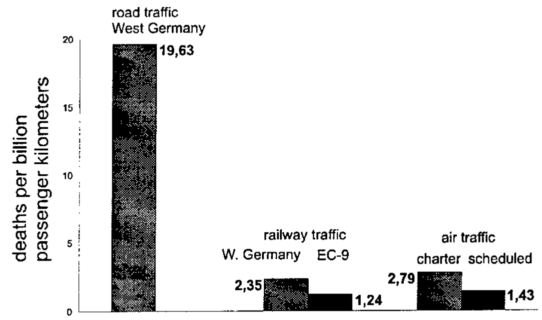

Figure 1: Average risk to passengers from 1974 through 1976 relative to 1 billion kilometers per person.

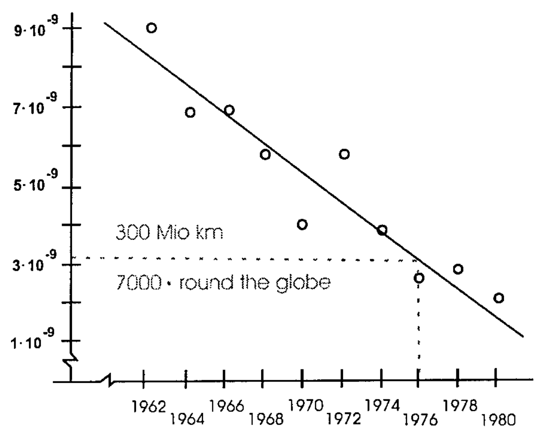

Figure 2: Accident statistics for aviation: fatal accidents per kilometer.

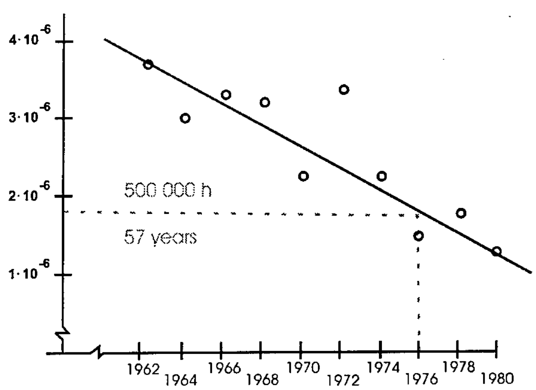

Figure 3: Accident statistics for aviation: fatal accidents per flight hour.

The starting point for the design of a technical device or vehicle often begins with the issue of the quality of the safety criteria. The technical solution depends strongly on this issue. Two axioms shall serve as the basis for the discussion of this problem: There is no such thing as absolute safety. Every technical and biological system can fail.

Every technical system is a compromise between contradictory requirements with regard to safety and efficiency.

The second axiom shall be explained with an example: The more stable an aircraft is constructed, the more robust it is against external influences such as turbulence and hard landings. However, as it becomes heavier, it also has a correspondingly reduced payload. An extremely safe aircraft can no longer fly.

If the basis for accident statistics is broad enough, meaning that a sufficiently large number of accidents have been analyzed and broken down according to cause, important conclusions can be drawn: Human error (crew, maintenance, air traffic control) is the cause of more than 80% of all accidents (Figure 4). The aircraft as a machine plays only a subordinate roll at 8%. If we want to increase the safety of air transportation, methods and procedures which support human beings in avoiding accidents must be improved. In order to solve these problems, it is helpful to look at the risk of accidents during the individual phases of flight (Figure 5). The most important and longest phase of flight, for which transportation aircraft are primarily designed, is cruise flight. However, such flights are only involved in 12% of accidents. All other accidents occur in the vicinity of airports. The most critical of the flight phases is the landing, with about 50% of all accidents occurring during this phase. This can also be seen in Figure 6 in which the difference between the performance capacity and the stress load of a pilot is shown. This may be an indicator of the risk. A detailed discussion of safety problems, as well as the methods of solving them can be found in [1]. The requirement of supporting human beings, especially during landings, results from these observations.

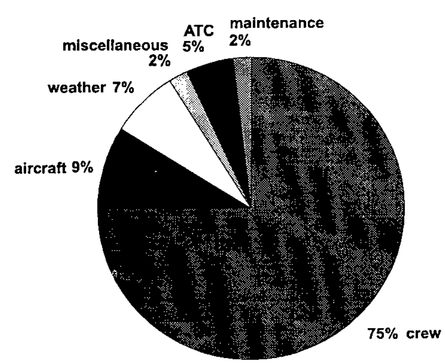

Figure 4: Break-down of aircraft accidents according to cause.

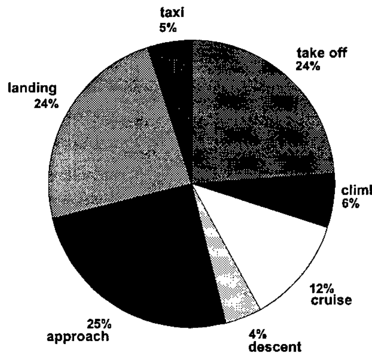

Figure 5: Risk of accident in different phases of flight.

A brief summary of the most important methods shall provide an impression of the possibilities and efforts which are being used in order to attempt to increase safety in air traffic.

Increase in performance capacity by means of:

selection of the most suitable pilots (both physically and mentally) – in other words, formation of an elite group

intensive training as preparation for the task

practicing critical situations in a flight simulator

high experience levels as a result of frequent flying

Reduction of stress by means of:

Good layout of the workplace. The cockpit of a transportation aircraft 30 years ago (Figure 7) and today (Figure 8) illustrate an increase in clarity, although an ever increasing amount of information is displayed and conveyed.

Processing of essential information. The information needed for individual phases of flight differs and is not all needed simultaneously. A drastic reduction of elements has been achieved with the audio/visual information transfer which is presently available. The possibility of confusion during operation of multifunctional displays or controls is a problem.

Automation, meaning relieving the pilot of secondary activities. The task of a pilot is increasingly shifting from a manual control task to one of system management.

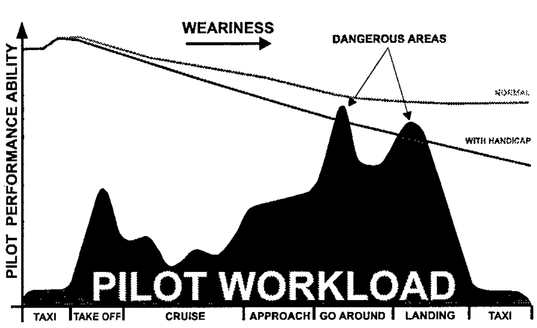

Figure 6: Performance ability and stress on pilot during the different phases of flight.

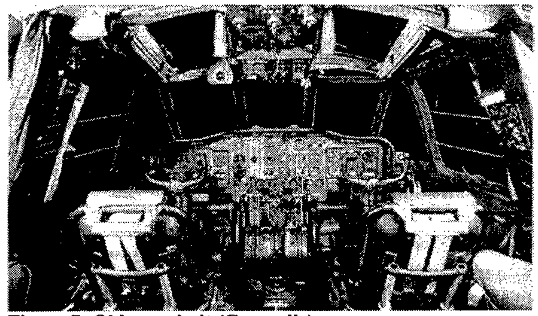

Figure 7: Older cockpit (Caravelle)

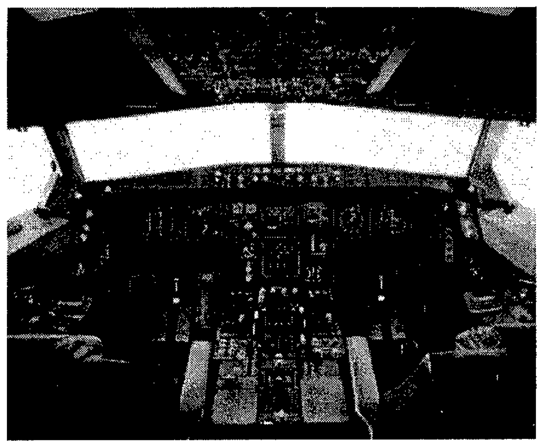

Figure 8: Modern cockpit (A 340)

2. Controller Structure

The controller structure primarily results from the guidance tasks, as well as the control of disturbances. The former are determined for the most part by air traffic: due to the usually high density of traffic, maintaining predetermined paths is an absolute necessity. Since the method of flying following waypoints has been commonly applied for more than 30 years, the paths consist of straight lines and arc segments. The paths must be reliably adhered to with an accuracy of better than 50 m as the vertical separation distance is 300 m. In the azimuth, the airways have a generous width of about 16 km. Consideration is being given to changing these procedures in order to gain air space. An azimuth accuracy of 300 m can be achieved with present technology. Errors due to inadequate sensors or faulty interpretation can be included in accident statistics as serious navigation errors. The precision requirements during the final approach, especially in adverse weather conditions, are substantially increased. There is a rule that the less visibility there is the higher the required precision and reliability of the technical system must be. For so-called blind landings (or more precisely:

CAT IIIa), a precision of 60 cm vertically and about 5 m horizontally must be proven at the runway threshold for maintaining the flight path. This must be achieved with a probable rate of failure of better than 10^{-7} errors per hour. When air conditions are calm, this precision is routinely, if also with effort, attained.

Figure 9: Influence of wind on flight path.

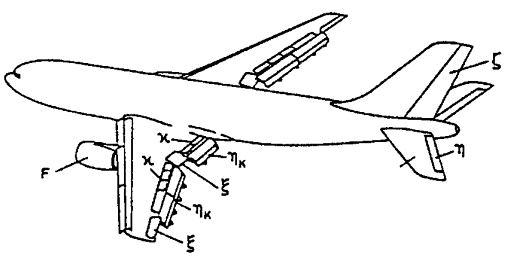

Figure 10: Controller outputs of an aircraft [3].

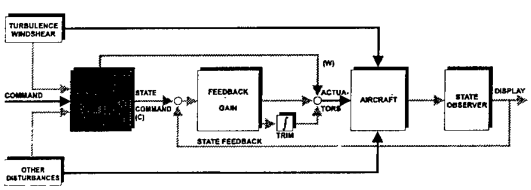

Figure 11: Flight controller structure.

If no external disturbances are present, the discussed precision is primarily dependent on the quality of the sensors. Precision in the decimeter range is possible globally with the new satellite navigation systems [2]. Disturbances in the flight path primarily originate from atmospheric disturbances (Figure 9). The higher frequency disturbances are caused by turbulence and also by storms. Low frequency disturbances are wind and wind shears. The disturbances are mainly spatially oriented and only become effective when flying through them. The higher the velocity, the higher the frequencies are. Typical unpleasant frequency ranges are between 10 Hz and characteristic vibration periods of ten minutes. The characteristic quantity is the wing surface of an aircraft relative to the aircraft mass. The larger the surface/mass ratio, the more sensitive the reaction of the aircraft. Even large aircraft can be substantially disturbed due to atmospheric disturbances. For this reason, one of the primary tasks of flight controllers is to control the effects of gust disturbances.

The motion of a rigid aircraft is described by means of a state vector with twelve elements:

$$\underline{x}^T = (\dot{\Phi}, \dot{\Theta}, \dot{\Psi}, \Phi, \Theta, \Psi, u, v, w, x, y, z) \qquad (1)$$

The best controller is the one in which all states are fed to all controller outputs. The usual controller outputs for an aircraft are (Figure 10):

- aileron ξ
- side rudder ζ
- elevator η
- thrust F
- wing flaps κ, η_κ

A good flight controller should consist of open and closed control loops [4] (Figure 11). Everything which is known about the controlled system should be processed in the open loop. Feedback primarily serves in the adjustment of eigen values and to compensate for control errors. Due to major changes in the controlled system which are dependent on the flight state, "trimming" (a weak integration of the state variables) has proven reliable. Trimming allows for shock-free switching between the different controller modes.

A special culture has developed in flight control during the last 70 years. Among other things, this is due to the fact that the airplane is one of the few controlled systems for which a description exists in the form of an independent technical discipline: flight mechanics [5]. It originates from the eighteen seventies. The major advantage of this discipline is an excellent knowledge of the controlled system, including relevant simplifications. Most phenomena can be described analytically. By means of an open loop controller, the substantial changes of the flight state can easily be brought under control. More current developments attempt to describe the inverse controlled system analytically [6].

For simple flight maneuvers (e.g., cruise flight), the flight motion can be separated into the longitudinal and lateral motion with 6 states each [3; 5].

Due to their extremely lightweight construction, aircraft are very flexible. Local buckling of skin plates is intentional. During your next flight, pay attention to the distortions of the wing surface. In order to describe the flexible degrees of freedom,

two states each are typically required for each of both of the types of motion.
With the exception of smaller, slower and inexpensive general aviation aircraft, the safety critical actuators are designed hydraulically and with extremely high requirements for control performance, precision, dynamics and reliability. Control performance of several hundred kilowatts at characteristic time constants of less than 100 ms are typical. The elevator actuator of the Tornado requires, for example, movements of the control surface of 20° during slow flight. In contrast, a rapid adjustment of the elevator of about 0.6° during a low level flight at about the speed of sound (for example, as a result of an error in a subsystem) leads to vertical acceleration of ten times the acceleration due to gravity, which neither the pilot nor the aircraft can sustain.
During the design of a flight controller, the dynamics of the control system must be considered. This usually more than triples the number of relevant states with respect to the rigid aircraft. State vectors with 50 or more elements are not unusual during the design phase.
Natural vibration modes of the flexible aircraft depend on the amplification of the flight controller. At lower amplification rates, especially in the rotational degrees of freedom, the aircraft can be considered rigid, while higher amplification rates influence the elastic modes. In the design of such controllers, there is the difficulty that the structure of the controlled system changes with the amplification rate. Certain amplification rates are often held constant during optimization tasks. In such cases, experience in design plays an essential role.

3. Hierarchical Control

After the somewhat general observations about safety, reliability and controller structures, the needs of pilots in relation to the requirements will now be discussed in more detail. Using the example of student pilot [4], in which, starting with simple tasks, one control level after the other is practiced, the hierarchical structure and the requirements for the relevant sensors shall be discussed. The four levels of the training and the control hierarchy are:

- stabilization
- heading and velocity control
- flight path control and
- flight maneuvers

a) Stabilizer

During the first hour of training, the instructor asks the student pilot to keep the attitude of the aircraft level with the horizon. He must measure roll and pitch and control them to the value zero. During conditions of good visibility, it is easy to observe the deviation of the symmetrical aircraft from the horizontal plane. The pilot can simply correct disturbances by means of the control stick in the training aircraft which generally exhibits well-damped oscillation characteristics. What can be considered easily controllable has been determined in many studies. The methods which are presently accepted world-wide are based on studies by Cooper and Harper [7]. The Cooper-Harper scale rates flight characteristics with something similar to school grades. Assessments which can easily be replicated are attained with well-trained test pilots. The eigenfrequency is plotted above the damping ratio in Figure 12 for the mode "fast oscillation of angle of attack". The shape of the "thumb print curve" is typical and provides clear statements on the optimal eigenfrequencies and dampings.
While it is easily possible to realize the optimal requirements for training aircraft with their small flight regime, this is no longer possible in the case of high performance aircraft. In this case, the pilot requires the support of a controller. The measurement of the angular velocity in all three rotational axes and the feedback of the signals to the corresponding aerodynamic rudder is the lowest level of the hierarchy. This type of controller is known as a "damper". The measurement of the angular velocity vector is performed with gyroscopes. There is presently a juxtaposition of mechanical and optronic gyroscopes- e.g., "fiberoptic" and "laser gyroscopes" – for which the constancy of the speed of light is used. As the failure of components in the sensors, in the controller and the actuators has fatal consequences for the controllability of the aircraft, the number of sensor and actuator chains is multiplied [1].

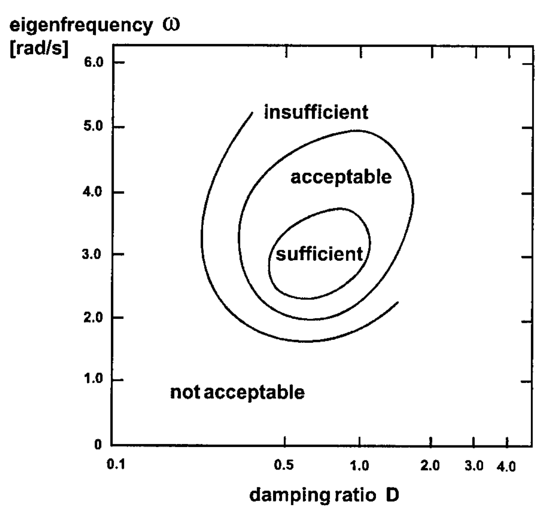

Figure 12: Requirements of oscillation of angle of attack

3 x 4 gyroscopes are necessary for a system of quadruple redundancy. The required consistency of measurement values of four gyroscopes in one axis in order to recognize the failure of an axis also during dynamic maneuvers has proven to be technically very complicated and costly.

It is easy to understand that the data bus systems represent are technically very complex and require a large effort in order to reliably connect the sensors, computers and actuators which are installed at great distances from one another. In a large transportation aircraft, distances of 30 meters and more of connection length in an electromagnetically unfriendly environment are common. International standards for parallel and serial bus systems have been in existence for a long time. However, the standards for civil and military applications differ.

In cases of bad visibility or for automation, the attitude is measured with the assistance of attitude gyroscopes. As the attitude gyroscopes can measure two Euler angles each, at least two attitude gyroscopes are required for the determination of the three Euler angles. In this case, the fourth measurement, which is superfluous, is used for monitoring failures and for increasing accuracy. As the attitude angles can also be derived from the angular rate by means of integration and a corresponding complicated coordinate transformation, the observation of values which are not measured plays an important role in flight control in order to be able to realize the high requirements with regard to safety and accuracy in a cost-effective manner.

The display of the Euler angles for pilots is performed in the so-called "artificial horizon". In modern aircraft this information is displayed in color on cathode ray tubes. Flickerless images with a frame frequency of 70 Hz (due to the dynamic environment), as well as extreme fluctuation of brightness in the cockpit, represent high technical requirements for the design of such Electronic Flight Instrument Systems (EFIS). Such systems are also priced accordingly (compare to Fig. 8).

One speciality of flight control should be mentioned at this point: the so-called "Flight Director". In this procedure, the pilot is integrated into the control loop. The pilot primarily has the task of an actuator. As humans react comparatively slowly, the actuator information is provided with a corresponding lead time. The display is realized in the form of a cross pointer. The pilot must keep the vertical and lateral deviation as close to zero as possible. Such a solution can easily be integrated into an EFIS. The reason for this method, which seems absurd at the first glance, has its origin in the human ability to recognize complex errors relatively rapidly. Consequently multiple actuators are not necessary. Relatively inexpensive systems for adverse weather approaches can be manufactured using this basic principle. A further advantage, in contrast to automatic flight controllers, is that the pilot stays in practice, thus solving a problem with en route flights half way around the Earth with few landings which could otherwise only be solved with great effort by means of flight simulation.

b) Course and Velocity Control

After the first lesson of maintaining the attitude has been learned successfully, the flying student is then given the task of additionally controlling course and velocity. This task requires that the aircraft is well damped. This additional task is to be performed with the same actuators as the damping. The associated modes have a frequency about ten times lower than the angular oscillation. The determination of the course angle is performed with the oldest navigation instrument known to man: the compass, which is more than one thousand years old. The compass is often coupled complementarily with a directional gyroscope for better dynamic characteristics of the compass. Such complementary sensor systems are typical for flight control. For reasons of cost, one sensor is responsible for stationary accuracy and the other, for the dynamic accuracy. If these systems are properly designed, there is no phase lag error.

Maintaining the desired flight velocity is very important for safe and economical operation of an aircraft. There are several optimum velocities each for optimum ascent, optimum fuel use during en route flight, as well as for economical flight. The maximum permissible velocity of the aircraft must not be exceeded. Otherwise, there is a danger of "flutter". These are structural instabilities which are excited through large aerodynamic forces and which lead immediately to the failure of components such as the stabilizers and wings. On the other hand, velocities which are too low are also dangerous as the flow separates and lift instantaneously stalls. As stall usually occurs asymmetrically on the wings, in such a case a strong rolling motion and a loss of altitude occur at the same time. This can be fatal especially during take-off or landing. Already at the normal traveling velocity of transportation aircraft of about 1000 km h^{-1} at altitudes of 12 km, the maximum permissible flight speed and stall speed are rather close together due to the low air density, such that the permissible velocity regime is very limited and the flight velocity must be maintained accurately. A further reason for precise velocity control is the horizontal separation of aircraft in narrow air spaces. In cases of extremely narrow separation, such as above the North Atlantic, aircraft fly at a constant distance, which requires that they travel at the same speed.

The current method for measuring velocity, which originates from the beginning of aviation, is based

on the measurement of dynamic pressure. The dynamic pressure is proportional to the air density and the square of the flight speed. The measurement, as well as the display, are nonlinear due to the measurement regime and the resolution.

c) Flight Path Control

After the first two lessons have been learned, the flying student can practice controlling the path: this means maintaining the altitude and the path above the ground. The flight altitude is usually measured indirectly using barometric pressure. The model of the standard atmosphere serves as a reference. Temporal and local changes in pressure must only be adjusted for during take-off and landing. The distance of separation between aircraft plays a primary role in cruise flight. However, the zeroing error due to changing ground pressure is negligible since it is the same for all aircraft. The transition procedures between standard pressure and adjustment to ground pressure are regulated precisely and legally for safety reasons.

A special problem in the measurement of the static atmospheric pressure is the flow around the airplane. There are few places on the outer skin of the wings and fuselage where the surface pressure is the same as the static barometric pressure of the undisturbed atmosphere. The ideal points of measurement move with altering flow conditions. The temperature and the flow velocity ought to be measured additionally as close as possible to the pressure port in order to determine the true atmospheric pressure. The complex flow equations are solved in so-called air data computers in order to determine the barometric altitude, flight speed and atmospheric temperature.

The distance of the aircraft from the Earth's surface can be determined by means of radar methods. Microwave radar systems are common. The accuracy, as well as the resolution, of laser altimeters is higher. However, the range is drastically reduced during adverse visibility conditions.

Simultaneous maintenance of altitude and velocity require variations in energy with the assistance of the engine thrust. Thrust may only be adjusted slowly and sparingly for a number of reasons, especially psychological ones, such that this controller output is relatively slow [4].

Maintaining the azimuth of the path requires a location sensor. Usually, location systems are based on radio navigation with differing accuracies and ranges. Due to the possibilities of satellite navigation, a revolution is about to occur in the field of location [2; 8].

Altitude and velocity are the parameters for the potential and kinetic energy of an aircraft. The control problem of maintaining the path shall be explained in further detail. The flight path azimuth is obtained from the lateral acceleration of the aircraft by means of simple integration. In order to generate this lateral acceleration, the lift vector, which is approximately the same as the aircraft weight, is tilted through rolling of the aircraft. The lateral acceleration is approximately proportional to the roll angle. There is almost no damping of this system which consists of two integrators. The difficulty of maintaining the path is comparable to balancing a vertical stick. If we remember, furthermore, that the roll angle is produced through double integration of the control moment, it becomes clear that the entire problem of lateral guidance is comparable to balancing two sticks which are placed one on top of the other. This double-stick model can easily be transferred to helicopters which are difficult to fly. In the case of airplanes, it is at least possible to accomplish that the sticks stay more or less connected by means of proper damping of the rotational degree of freedom. During good visibility conditions, the lateral velocity of the aircraft above the Earth's surface can be estimated. During adverse visibility conditions, this is no longer a possibility and the corresponding damping must be displayed in the flight director by means of measurements or observations.

d) Flight Maneuvers

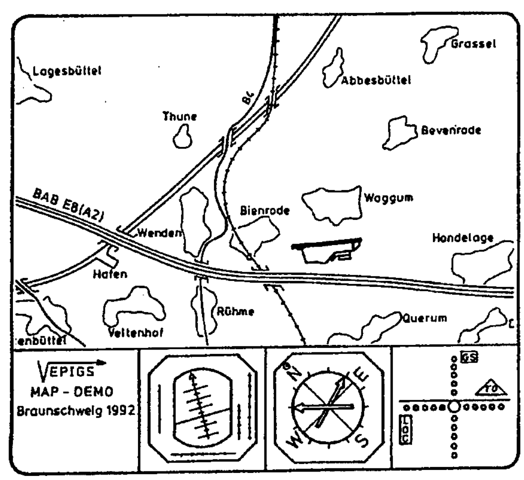

Figure 13: Digital map.

The last and most difficult lesson is the precise flying of maneuvers. It requires the mastering of the first three lessons. Such maneuvers occur during curved noise-reducing approaches. The difficulty is increased even more by time-accurate flying (4D). As a result of currently available experience, such maneuvers can only be performed fully automatically by a pilot, who basically monitors the

procedures. In such cases, it became apparent that also during fully automatically flown curved approaches, the pilot requires a corresponding display of the state vector in order to be properly informed. The current highly abstract type of display for instrument flight in aircraft (in which the flight path consists of polygons) must be supplemented with a better display of information, such as a digital map (Figure 13).

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FLIGHT MANAGEMENT SYSTEMS IN THE NEW AIR TRAFFIC MANAGEMENT, (ATM), ENVIRONMENT.

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Abstract

The new ATM environment will place additional requirements on Flight Management Systems. It will be necessary to provide data on position and aircraft trajectory to be used by other aircraft and by ground based air traffic managers, at a level of availability and integrity which is consistent with the safety of the air traffic system. Corresponding data from the other aircraft in the airspace must be analysed in order to identify potential conflicts.
The algorithms for the resolution of potential conflict with other aircraft must be based on a common strategy which applies throughout all aircraft.
The way in which such conflict resolution could interface with the FMS flight plan and with optimisation are discussed.

1. Introduction.

For the last twenty years the Flight Management System has been an element in the avionic systems of an increasing proportion of commercial aircraft. During that time the sophistication and power of the Flight Management Systems has increased, but the concept has remained substantially unaltered.

The Flight Management System was introduced as an aid to the flight deck crew at the time of the reduction from three to two crew operation. Its essential feature was to provide a system which could accept the concept of the total route to be flown and could be responsible for the guidance of the aircraft along that route. In the environment of increased fuel, prices it also became the focus for the means of flying the aircraft in an economic way.

The Flight Management System became the location for the synthesis of several independent methods of position determination including IRS, DME, VOR to provide a best estimate of aircraft position. The interface with the flight deck crew allowed routes to be planned and changes to the routing to be introduced. The effort of doing this was considerably reduced by the inclusion of a navigation database within the flight management computer. The crew were then able to identify whole routes or route segments directly from the database without the need to type in a series of geographic coordinates.

The display interface provided the flight deck crew with information on the position of the aircraft with respect to the route and predictions concerning progress toward the destination.
The performance database, containing airframe and engine data allowed the cost of routing alternatives to be compared.

Additional features have included, control to achieve a time of arrival constraint, the inclusion of minimum safe altitude information, the use of GPS navigation data, the interfacing to datalink information from ATC.

The concept of the Flight Management System has however remained constant throughout. It is the means whereby a single aircraft can steer its way through a route which is defined by constraints, waypoint sequences, cruise

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altitudes, altitude and speed constraints at waypoints, procedures, etc., plus constraints applied by the ATC controller, in a manner which achieves the goals of economy.

The FMS identifies the most economic way of flying the route given these constraints and enables the flight deck crew to evaluate the benefits or otherwise of potential changes to the routing either lateral or vertical.

The anomaly has been that over the years more and more aircraft have become fitted with FMS all of which are capable of routing the individual aircraft independently of the existing airway structure, and yet all have been constrained to follow this existing structure.

2. New ATM Concept.

The new concept of ATM is to increase the usable capacity of the airspace and allow more efficient operation, by allowing aircraft to fly outside the present airway constraints and to utilise more direct routings between origin and destination. Additionally aircraft may be allowed to fly at whatever flight levels they determine to be most efficient for their operation.

However some constraints will remain.

In those areas for which the capacity of the take-off or landing runways is the limiting feature, aircraft will necessarily have to accept some constraints.
These may be, not being able to take-off at the desired time because of the presence of a queue of other traffic waiting to use the same runway.
There may be areas of congestion as aircraft arrive in the terminal area to begin their approach and maintaining separation criteria may result in aircraft having to change their routing, speed and altitude , or a delay may be necessary because of a queue of other aircraft waiting to make their final approach..

During en-route flight, flight-level constraints may be necessary to maintain separation from crossing traffic.

It is possible therefore that although the en-route portion of the flight may be accomplished with fewer constraints than at present, the savings, which are obtained from that and the more direct routings, may be eroded in areas of congestion at the origin and destination.
The significance of these to the overall economics of operation will depend upon the average duration of the flight. In Europe where the average flight duration is of the order of 90 minutes then any en-route savings could be easily be dissipated by terminal area delays. On trans-oceanic routes the economic significance of the terminal area delays will be less, but none the less such delays will be annoying to the passengers.

Strategic constraints on traffic volume will continue to exist. These may take the form of controlling the number of aircraft planning to land per unit time to the capacity of the particular airports to accept such volume. This is likely to be effected primarily by the control of take-off times, because such controls can be introduced at almost zero fuel cost.
Such strategic controls will have to be implemented by the ground portion of the Air Traffic Management system which has a visibility of the whole scene of aircraft movements.

However since aircraft motion will suffer uncertainties due to, last minute delays in take-off, weather variations, the actual route flown, etc., interactions with other traffic will occur. In consequence strategic planning and control is not able to prevent all potential conflict between aircraft. A function of conflict detection and resolution will need either to be present in the aircraft or present on the ground from where it can be implemented by ground controllers requiring particular aircraft

manoeuvres or flight plan changes.

Whichever method is applied, the Flight Management Systems constraints will be dynamic and will be the result of specific conflict. That is they will be related to the presence of other traffic rather than being imposed as away of making routing invariant of other traffic.

However whether potential conflict is detected by aircraft individually and resolved mutually between the involved aircraft, or whether the resolution is imposed by the traffic controllers has a significant impact on the Flight Management Systems.

3. FMS Implications

The changes in the ATM concept mean that, apart from the setting of overall flow rates, individual aircraft will be able to follow their own preferred routing. Potential conflict between aircraft is maintained by actively monitoring for such conflict and then introducing remedial action to maintain an adequate separation.
This is in contrast to the existing situation in which the airspace is structured to maintain separation and monitoring is limited principally to checking that aircraft are maintaining the allocated routings.

3.1. Monitoring

Within the proposed ATM system safety is maintained by actively monitoring for conflict and reacting to resolve that conflict. Monitoring requires information to be provided by each aircraft in the airspace and an analysis of this information in the form of a forward projection in time to see whether separation constraints remain satisfied. This process is then repeated at suitable intervals. If the forward projection indicates that a separation constraint will be infringed then some or all of the affected aircraft must alter their flight path in a manner which will either remove the projected infringement or at least make its projected time of occurrence later.

The resolution strategy may be imposed in an open-loop manner, (i.e. an algorithm is applied), or it may be applied in a closed-loop manner in which the consequences of applying the algorithm are examined, by a second forward projection in time, and only if that projection shows that the conflict situation would be removed or substantially alleviated is it applied. If the projection shows that the conflict will persist then a second level of resolution algorithm could be applied.

The data upon which the conflict monitoring is based arises from the Flight Management Systems in the individual aircraft.

The required data will include, Present Position and estimated variance, Altitude or Flight Level, Speed, Track, Control mode with appropriate parameters, Flight Plan for the next period of time, (say, 20 minutes), it may also include status of the aircraft and its systems, (e.g. descending due to all engine flame out), which may limit that aircraft's ability to make flight path changes.

The principal impact on the Flight Management System relates to the integrity requirement and to the speed of operation.

3.1.1. Integrity

The detection and resolution of potential conflicts can be disabled by defects within the equipment fit of any of the aircraft involved. The possible situations can be summarised under three headings:

- The silent aircraft

In which one of the aircraft does not annunciate to the others the information which is necessary for them to detect conflict. (An extreme case of

this would be the presence of an unequipped aircraft in the airspace.)

Clearly if such information was lacking the ability to detect the existence of potential conflict would be compromised. To avoid this, the ability to provide such information must exist within each aircraft with a level of probability which does not conflict with the requirement for safe operation of the airspace. This is likely to require a greater level of Flight Management redundancy than is provided at present.

- The lost aircraft

In which one of the aircraft does not know its position accurately and therefore provides incorrect information to the others in that airspace.

The potential to provide misleading information must be made sufficiently remote to not compromise the safety of the airspace. This will require more redundancy in position determination than exists within Flight Management Systems today.

- The disabled aircraft

In which one of the aircraft is unable to take normal action contributory to resolving conflict because of some failure which has occurred.

The important characteristic is that the ability to communicate the information should not be influenced by the defect itself. Segregation and independence of the means of detecting and communicating the status information must be maintained in presence of a defect.

3.1.2. Speed of Operation

An increase in the redundancy level can ensure that the information necessary to detect potential conflict is available, or when such information is known not to be available can ensure that this is annunciated to the other aircraft in the airspace. However it is not certain that every potential conflict can be resolved simply.
(Simple resolution is used here to mean that the initial actions to resolve do not cause the occurrence of another potential conflict within the same time frame.)

The problem of resolution clearly becomes more difficult as the density of aircraft in the airspace increases. Thus as aircraft approach the terminal area the degrees of freedom for resolution of conflict become more restricted. This will be reflected in the complexity of the algorithms for resolution.

At a particular time, an aircraft has available for analysis, data from other aircraft whose distances lie on or within the boundaries of a spatial envelope which surrounds the aircraft. The boundary defines a minimum time that aircraft at the boundary would take to reach the subject aircraft. The detection algorithm operated in the subject aircraft extrapolates the path of each of the other aircraft and monitors the distance between each of the other aircraft and itself, over time. The time horizon will extend to the shorter of either, the time of a future conflict or, the time limit of the input data projection.

If the conflict detection is being conducted within each aircraft then, since each aircraft is in a separate location and therefore has a separate boundary envelope of interest, there may be several independent potential conflicts detected.

Thus if the set of aircraft is A_1, A_2, ...,A_i, ...A_n, then A_1 may detect a potential conflict with A_2 which will occur at time t_{12}, but A_2 may detect a potential conflict with A_i which will occur at time t_{2i} ,which is earlier than t_{12} .

This non reciprocal conflict detection may propagate through the aircraft set until

eventually there will be a reciprocal pair which corresponds to the earliest predicted conflict in the airspace.

Thus when A_1 makes its conflict avoidance manoeuvre it may be that A_2 is in process of invoking a manoeuvre to avoid the potential conflict with A_i.
In consequence at the next iteration of the conflict detection the potential conflict between A_1 and A_2 may or may not have been resolved. It may, for example, have been made worse as a result of the aircraft A_2 planned manoeuvre to avoid the conflict with A_i.

For a given aircraft density the chances of this overall system remaining stable is clearly a function of the iteration time which can be achieved in the conflict detection and conflict avoidance cycle.

3.2 Algorithm Complexity

The algorithms to be applied for conflict resolution must be able to be applied independently by the involved aircraft. In consequence the fundamental rules for conflict resolution, to which each conforms, must be a standard set which apply to all circumstances. These rules for resolution must remain constant over time so that the actions to resolve conflict taken by the aircraft involved, complement one another whether the aircraft are using algorithms designed a decade apart or exactly the same algorithm.

It seems intuitively plausible that if the traffic density is increased there will come a time when a given set of algorithms, being evaluated at some particular rate, is unable to satisfactorily resolve certain conflict situations. Given that the local traffic density could exceed the threshold for satisfactory operation even if the average density is maintained at some lower level, for what set of circumstances would a given set of algorithms be validated?

It would appear essential that there is an overall ATM strategic plan which limits the traffic density in the airspace without requiring any detailed knowledge of the routings which individual aircraft will follow. Algorithms can then be qualified for use up to some multiple of that average density.
However aircraft equipped with algorithms qualified for different maximum traffic densities could well co-exist in the same airspace. In consequence, knowledge of the capability of the equipped aircraft needs to be available to the ground-based air traffic managers who would monitor the temporal fluctuations of traffic density and themselves intervene if any algorithm limits were being approached.

3.3. Interaction of Conflict Resolution and Route Planning

The task for which each operator is using its aircraft is to transport the payload to the destination safely, economically and on time. The consequence of other aircraft being present is potentially to introduce delays and therefore to make the operation less economic.

The interaction with other aircraft may occur, on the ground during push back and taxi, waiting for availability of the take-off runway, in the terminal area during climb, en-route, in the terminal area during approach and landing, on the ground during taxi and at the arrival gate. At any point having to defer to an other aircraft carries a potential penalty in terms of the economics and timeliness of the service.

In consequence each operator will seek to minimise such effects on their own particular aircraft.

The FMS is the centre within each aircraft which has the data and the capability to calculate the consequences of delays, diversions and constraints on the timing and economics of the flight. In current operation, it enables the

flight deck crew to assess the consequences of any constraint applied by ATC and to propose alternative flight plan changes which would improve the economics of the flight for that aircraft.

Any change which is imposed from outside will be treated like this. If it imposes a penalty then an alternative will be sought by the flight crew. If it relaxes a previously applied constraint and improves the economics of operation for that aircraft it will be accepted.

However because the existence of a potential conflict with other aircraft does not itself have a consequence which can be quantified within a Flight Management System, then any action to resolve such a conflict will be perceived by the FMS as something which alters the economics of the operation in a negative way.

Could conflict resolution be treated as a Flight Management Function?

Suppose that when a potential conflict is detected the flight plan is altered by imposing a constraint on that point in space/time, e.g. At the identified conflict time the aircraft must be more than x miles from the potential conflict point, or more than w thousand feet above or below it, or that the aircraft must arrive at the potential conflict point either more than y minutes before or y minutes after the conflict time. Could conflict be avoided?

Clearly as a static problem this could be solved by the FMS. However the other aircraft with which the potential conflict will occur also possesses an FMS and to this FMS also a corresponding flight plan constraint will have been applied.

In seeking to optimise the flight plan there is no logic which would prevent the two FMSs adopting mutually cancelling resolution manoeuvres. This is fundamentally because the strategy within each FMS is to optimise the remaining portion of its own flight in the presence of this imposed constraint and the two aircraft are engaged on different flights and therefore have different flight plans The constraint is static, there is no information about why the constraint exists or about the flight plan of the other aircraft.
Clearly it is impractical for aircraft to exchange their flight plans, performance models and cost criteria so that each can solve the "two aircraft problem".

In consequence it is considered essential for the resolution strategy to be independent of the FMS flight planning function and to be a function only of the geometry of the situation.

The instruction to the FMS may then be to introduce a waypoint, or series of waypoints, together with altitude and time constraints in order to steer clear of the potential conflict. The other aircraft will have, depending on the situation as perceived by it, done nothing, made a complementary manoeuvre, or possibly, begun a manoeuvre to address a more immediate potential conflict between itself and another aircraft.

Clearly the further ahead in time that a potential conflict can be predicted the less abrupt can be the manoeuvre to resolve the situation. The manoeuvre will be a function of the state of the two aircraft at the potential conflict point.

The interface between the conflict resolution and flight planning is illustrated in Figure 1. A potential conflict is detected by an analysis of the data received from other aircraft in the airspace together with the predictions for the flight path of own aircraft. If the algorithms applied to this data detect a potential conflict then the conflict resolution algorithm imposes a modification to the flight plan of own aircraft. This may be in the form of an altitude constraint, a speed constraint, a new waypoint or waypoint sequence or some combination of the above. These changes are introduced into

the flight plan and a new set of flight plan predictions run. Normally this will serve to clear the conflict or replace it by another at a later time.

If there is no potential conflict, either because the original conflict has been cleared or because on the basis of present information none exists, then the FMS is free to optimise the flight plan on the basis of the current aircraft state and the latest meteorological data. This optimisation proposal may take the form of a Temporary Flight Plan, that is for the moment it is separate from the Active Flight Plan to which the aircraft is being controlled. The consequences of the Temporary flight plan are revealed by running the Flight Plan Predictions on that plan. These predictions can be examined in conjunction with the data from the other aircraft to see whether potential conflict would ensue. In the absence of conflict the Temporary Flight Plan can be promoted to Active. On the other hand if the detection algorithm indicates one or more potential conflicts the Temporary Flight Plan can be cancelled.

4. Situation Awareness

Existing Flight Management displays are designed to provide the flight deck crew with the awareness of where the aircraft is with respect to its flight plan including the constraints which it is required to meet. Flight deck crews obtain there awareness of other traffic by monitoring ATC voice communication. However in the new ATM situation the data to be appreciated will be more complex partly because of the additional freedom which aircraft have to follow their own desired routing and partly because much of the existing voice communication with ATC will be replaced by data link messages. Potentially the conflict detection functionality of an aircraft's Flight Management system has all of the data relevant to supporting situation awareness. However the format and context for the presentation of this information which is most readily intelligible to the flight deck crew remains to be determined and will require perhaps additional displays and certainly additional display logic compared with those available in today's Flight Management Systems.

5. Conclusions

The provision by each aircraft in the airspace, of its true position, velocity and future path predictions to all of the other aircraft in order that they can each determine whether a potential conflict exists, is an essential element in the maintenance of flight safety in the new ATM environment. If such data is incorrect or is not provided then the operational safety within that airspace is prejudiced. Failure by any one aircraft diminishes the level of safety for all of the aircraft in the airspace.
To ensure that such data is validated before it is transmitted and that a failure of transmission can be, at least, annunciated, requires that a sufficient level of redundancy is available at all times. This is a more severe requirement than is currently addressed by Flight Management Systems and will require the provision of at least one additional level of redundancy.

If one aircraft has a failure which results in it losing the ability to detect potential conflicts, this is less serious since each involved aircraft will separately manoeuvre to avoid the conflict. However two aircraft each failing to detect a potential conflict between them could seriously reduce the operational safety. In consequence there will need to be monitoring of the conflict detection function so that when a failure is detected it can be rectified when that aircraft is next on the ground. This will serve to reduce the time at risk associated with such a failure.

Similarly the calculation and implementation of a conflict avoidance manoeuvre must be monitored. Undetected failures which caused

reversal of the sign of the conflict avoidance manoeuvre could have a serious effect on the operational safety and may require additional redundancy to reduce the probability of their occurrence.

The summary of this is that there may need to be significant changes in the redundancy level associated with Flight Management Systems in addition to the increased functionality which is required by operating in the new ATM environment.

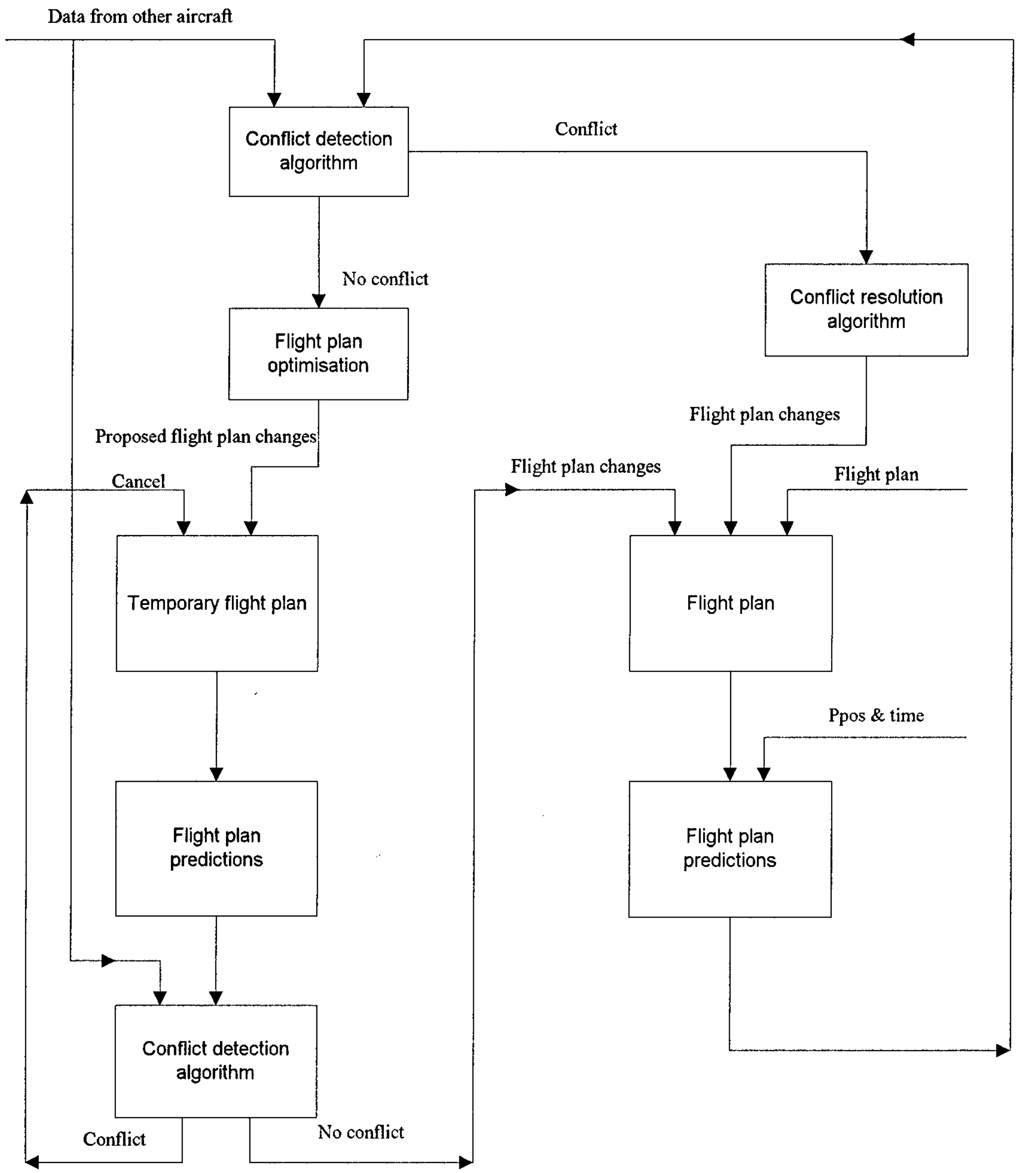

Figure 1

Relationship between Flight Planning and Conflict Resolution

IMPACT OF AUTOMATION ON THE OPTIMISATION OF THE FLIGHT

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1 - TRAFFIC GROWTH

In 1990 a study commissioned by EU/DG XII the Air transport demand was estimated to rise by 4.5 % per year. - implying an almost threefold increase in air transport demand in the next 25 years - while cargo traffic was expected to grow by about 8 % per year. Since that time, the real increase was above 5 %.

In a EUROCONTROL report entitled « Time-based Air Traffic Control in an Extended Terminal Area » a summary of the expected rate of growth as perceived by the Organization was given: average annual passenger growth evaluated at 6 % in Europe with a peak at 10 % around 1999. At such a rate the number of passengers would double by the year 2000 and triple by 2010. The rate of growth of freight was quite linear between 1985 and 1990 (about 12 %) with a temporary stagnation around 1991.

From these data we will accept that *the 1995 traffic rate is expected to double between 2008-2010 and triple by 2015.*

Short-haul traffic is expected to decrease *at least in Europe* and in some other congested parts of the world owing to the rapid development of rail and highway networks. Scheduled air traffic between cities 400-600 km apart will gradually disappear over the next 15 years. On the other hand, very large aircraft (600-800 passengers) will become commercialised, probably around 2005-2008.

2 - MAJOR TECHNICAL EVENTS IN THE NEAR FUTURE

In the near future two major innovations will appear: the *automatic data transmission* sub-systems and the *GNSS-1* (Global Navigation Satellite System). The automatic data transmission comes from the CNS/ATM (Communication Navigation Surveillance/Air Traffic Management) set up in 1991 by the FANS (Future Air Navigation System). The innovation is the capability of transmitting data through the ATN (Aeronautical Telecommunication Network). The constaints are :

to be able to use the public or private telecommunication networks because messages re-transmitted by satellites can be relayed by these networks

inside the civil aeronautical community, to be coherent with the other means of data transmission.

In 1987, ICAO asked the SISCASP (SSR Improvement and Collision Avoidance System Panel), in charge of the standardisation of SSR Mode-S messages to develop protocoles insuring the interoperability of all the data transmission systems used in Aeronautics. Protocoles comply with the OSI (Open System Interconnection) de l'ISO.

For the *automatic data transmission*, three systems will be implemented soon:

a) theVDL (VHF Digital Link). In fact, it is already in use on a private basis (ARINCS and SITA networks, ARINCS 622 protocole) for Airline operations. Three modes will be available:

* mode 1 which is the development of the ACARS-SITA bandwidth and protocoles OSI
* mode 2 which corresponds to a rate of 31.5 kB
* mode 3 which uses the same layers as mode 2 but with an access mode TDMA (Time Division Multiple Access). This system accepts both voice and data.

For modes 2 and 3 the bandwidth is 25 kHz with D8PSK modulation

Experiments are in process for flight plans transmission.

b) the data package both air to ground and ground to air associated with the SSR Mode-S. Up and down messages can be exchanged between the plane and the controllers each time the radar lobe hits a plane. Frequencies: up 1030 MHz; down 1090 Mhz. The on-board transponder is also used in the T-CAS and ADS-B to broadcast position (and possibly other parameters) on request (T-CAS) or on a periodic mode (ADS-B). Messages are 56 bit long; they can be extended to 112 bits. The data to be transmitted are not yet standardized!

Mode-S radars should be interconnected for exchanging data; they use the GDLP (Ground Datalink Processor) Experiments have started in 1991.

c) the satellite networks, a part of CNS. Today on-board public telephones are already installed in some planes. They operate on 1670-1675 Mhz. A particular sub-system in CNS concept is the ADS (Automatic Dependent Surveillance) and, namely, the ADS-C (C for Contract). In this system, identity, position and other data are transmitted on a periodic basis. The period can be adjusted according to the phase of the flight. It is recommanded that position comes from the GPS (or GPS-GLONASS) receiver, eventually checked or coordinated with other data available on board. A performance index depending of the on-board equipments is added to the message.

Another innovation which is coming concerns the reduction bandwidth for voice VHF channels from 25 kHz to 8.33 kHz (the modulation will still be in amplitude, but with the use of double side lobes modulation). The number of channels

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will be muliplied by three (in Europe, implementation on January 1st, 1999)

The potentialities offered by these systems must be optimized as soon as possible.

First, research projects aimed at developing senarios for exchange of data between the plane and Control should be developped soon because the automatic data transmission may modify deeply the crew / controller behaviour. Some experiments have been conducted in 1991 under a Eurocontrol program with a Mode-S radar located in Bedford (UK). Experiments are in process with Mode-S radars located at Brétigny and Rouen (France). Coordinated experiments should be undertaken because it is not only a national problem but a world wide problem.

Secondly, it is important to decide what kind of data should be transmitted. For example, it would be possible to show the local traffic on board; it is not obvious that it would be a « plus » because ambigous situations may appear between the instruction transmitted (automatic mode) by the controllers, the T-CAS indications and what the crew is willing to do.

The second major innovation, the GNSS-1 and later GNSS-2, has a dominant importance. It will be commented in paragraph 5. We think that during the last 50 years there were only 2 or 3 technical jumps of such an amplitude (we can mention the radar outcome for civilian use 1950, the jet engines 1960 and the electronic control of the plane 1980).

The two major innovations to come soon, if well managed, will lead to a *simplified aircraft*, to a *more automatized than present aircraft* and to a *safer Air Transport System.*

3 - KEYWORDS

Safety: actually 0,5 10^{-7}/h it should reach 0,5 10^{-8}/h within the next decade, mainly for mediatic reasons. Air safety is good; a little below train safety if *time* is the parameter considered (for durations of less than 5 h), a little better if *distance* travelled is the considered parameter (for distances above 5000 km).

Efficiency: it involves attractive time tables, *regularity* (on-time with regard to the schedule) and *comfort* not only during the flight but also during the walks inside the terminals and the luggage service. Efficiency concerns the aircraft manufacturer, the airline operator and the air trffic control

Environment: a strong request already exists : to reduce noise and to minimize chemical pollution (short term CO, CO_2 and longer term NO_x) both in flight and during the movements on the platform (Fig 1 from Ref [1]). Some countries already modulate the landing taxes according to the type of engines used.

In the next paragraphs we will evaluate the impact of automatisation on these three items.

4 - DIRECT IMPACT OF AUTOMATISATION ON SAFETY OF THE FLIGHT

4.1 Typical examples

a) Some 30 years ago, once the efficiency of ILS was proven, the cross-pointer instrument was replaced by a « zero reader » instrument: go toward the pointers; whence at zero, maintain them to zero. Once the pointers are at zero the meaning is « your situation is correct, maintain the cross pointers at zero ». It was a tremendous progress because for an approach without visibility the pilot's workload is high. The mental « computations » that the pilot had to perform are done automatically by a simple computer (analogous type) which solves a second order differential equation fed by data from on-board instruments (the ILS signal, the compass and the artificial horizon). Pilots are more confident in this type of instrument. However, for safety reasons ILS deviation signals are indicated on board on the PFD (Fig 2a).

b) More recently, due to electronically controlled plane (A 320 : 1988, B 777 : 1996) it is possible to unify the control law in pitch and roll. This is the C* law: a given displacement of the stick (lateral sticks in the Airbus family) leads to a given load factor for the plane whatever the velocity, the altitude and the atmospheric parameters are. *This law is unique during the whole flight* except during the flare at landing. Effectively during the last instants prior to touch down the main parameter to be controlled is the pitch attitude (transient phase between the airborne phase to the rolling phase). If the landing is performed in CAT-3 (necessarily in an automatic mode) the evolution of the control law is gradual according to the signal given by the radioaltimeter.

c) In case of panic, the crew may forget about the minimum safe indicated airspeed (which could vary between 1,3 Vs and 1,12 Vs, Vs being the stall speed). In fact the interesting part of the flight domain appears on the Primary Flight Display (see Fig 2). It is mandatory to avoid reaching Vs(stall velocity). Automatic control of the engine (FADEC: Full Authority Digital Electronic Control) receives data from the angle of attack probes and react in order to avoid an angle of attack greater than the one reached at 1,12 Vs (stick shaker speed).

d) The duality stability / manoeuvrability corresponds to a « positive balance » of the plane in any phase of the flight. However, positive stability implies a negative lift on the rear empennage which should be compensated for by an equivalent additional lift on the wings and, thus, an additional drag. In modern aircraft, the stability margin is reduced due to high efficiency automatic pilot. But

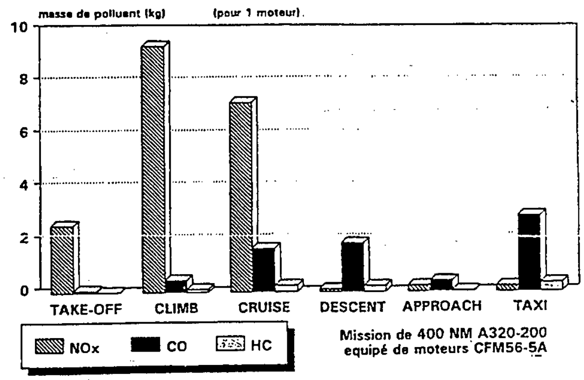
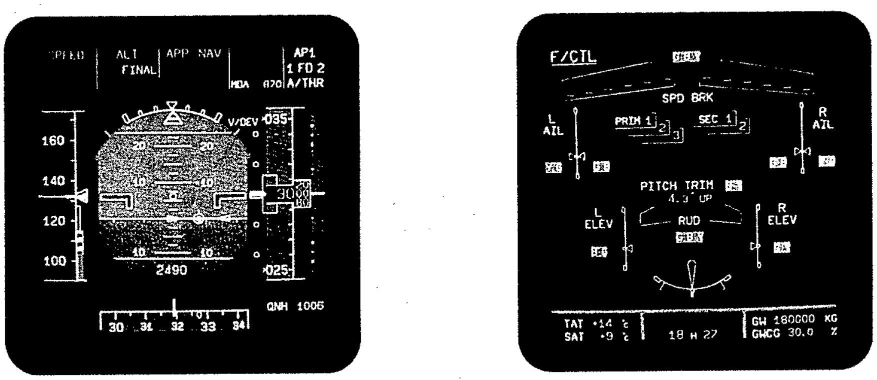


Fig. 1 Importance of the CO mass ejected during taxiing [from Ref. 1]



PFD and ECAM : normal law

Fig. 2 Primary Flight Display (A340)

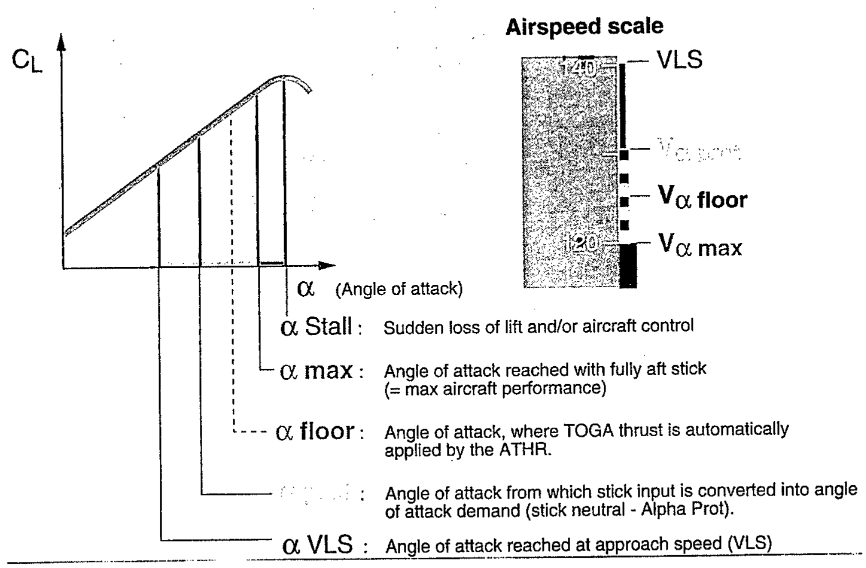


Fig. 3 Protection for high angle of attack

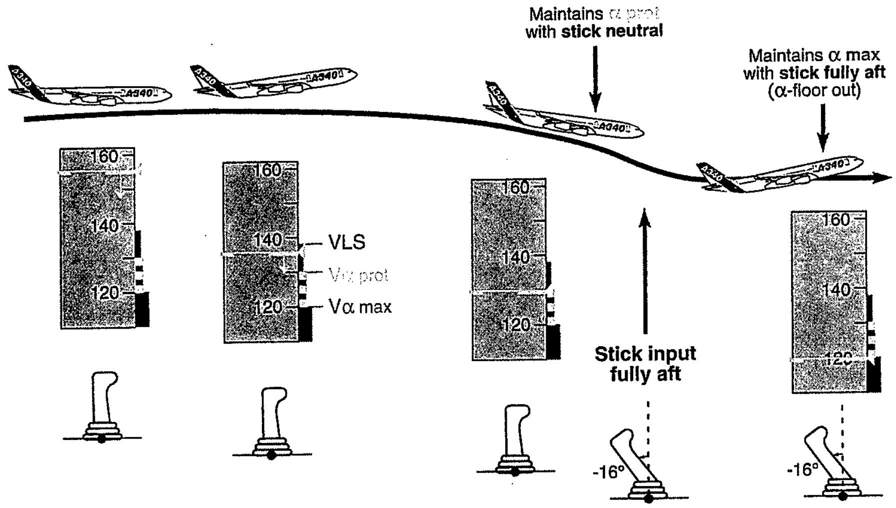


Fig4 Typical manoeuver : protection for high angle of attack

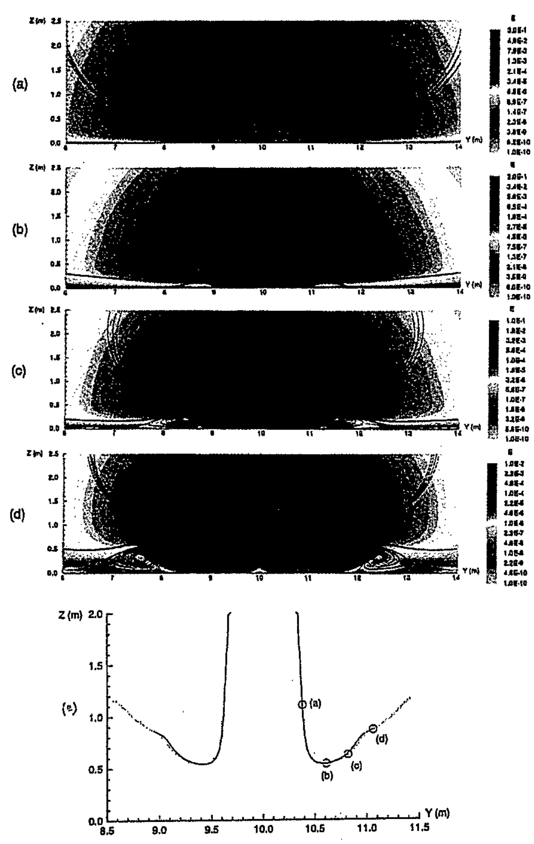


Fig. 5 Evolution of wing vortices in the vicinity of the ground

it is possible to reduce the negative lift on the empennage by transfering fuel from the tanks which are located in the wing to the rear vertical empennage. For a specified positive balance the negative lift on the empennage is reduced and, consequently, the additionnal drag on the wing. Thanks to the experience gained with Concorde (the fuel transfer is mandatory prior to reach M=1) the A310, A330 and A340 have automatic fuel transfer.

To conclude this paragraph let us say that, in modern aircraft, the flight domain appears on the PFD, at least in the vicinity of the present flight state. On the IAS indication (vertical scale on the left) the amber and red signs indicate 1,3 Vs and Vs at the altitude of the flight. At the other extremity of the speed scale the V_{MO} (maximum operational speed) and the V_{NE} (never exceed) are quoted as well. In addition, the speed which will be reached by the plane *10 seconds later if there is no action on the controls* is indicated by the arrow which is attached to the pointer. Fig. 3 shows the "protections for high angle of attack". Fig 4 shows the speed indications for a typical manoeuvrer.

4.2 Atmosphere - aircraft interaction

The « standard atmosphere » is used for a preliminary design of a plane. The atmosphere in which the plane flies is quite different from the standard atmosphere. In the troposphere vertical and horizontal air motion exist. The vertical local velocity may reach 20 to 30 m/s in cumulo-nimbus clouds. In the statosphere vertical motions are rare and not intense while horizontal motions with high velocities (100 m/s or more) are frequent (jet steams); they are like tubes of some hundreds of meters in diameter; the flux may be laminar inside but strong turbulence is present on the boundary. To be certified, an aircraft should cope with the « vertical gust » of the « specifications » (FAR or JAR in Europe; the profile of the gust has a shape in « 1-cos ») and with a von Karman spectrum (it concerns structure fatigue mainly).

It is far from sufficient. In the troposphere some phenomenas, called *downbursts*, which have been discovered and explainded by Theodore Fujita (University of Chicago) in 1975, were responsible for the loss of some 5 commercial aircraft each year. Downbursts result from the sudden instability of a cold mass of air due to a decrease of the vertical ascending flow of air produced by evaporation. When the mass of cold air collapses, the center of this down flow may be laminar and vertical velocities as high as 40 kts have been detected. Arriving on the ground, a giant toric vortex is created. It becomes larger and larger, moves along the surface while a new vortex is generated. Th Fujita has studied many accidents which were considered as « pilots errors », for example Continental 426, Denver Aug 7, 1975, or Royal Jordanian 600 at Doha, May 14,1976.

Since that time, much research and experimentation have been developped. Modelisations are very often correct. The detection either on the ground or on-board is difficult because the secondary phenomenas induced by the primary one. In addition, real experimentations (for example identification of the axis of the downburst and the location of the centers of vortices) are difficult because of the rarety of such phenomenas.

Nevertheless, modern aircraft are equipped with on-board warning system. Airbus philosophy first defines a *wind severity factor SF* which reflects the instantaneous loss of total energy due to global shear (longitudinal and vertical)

where : $$SF = \frac{dW_x}{dt} - \frac{g}{V} W_z$$

W_x longitudinal wind (negative if headwind)

W_Z vertical wind (negative if downwind)

V indicated airspeed of the plane (IAS)

SF is filtered and compared to a fixed threshold, typically 0,13 g (which corresponds to 2,5 kts/s). A 4 s lag was found the best compromise to avoid false alarms with a probability of less than 10^{-6} per landing (this the probability of encountering a windshear)

However, for better warning and escape manoeuvre capability, the warning system is a compromise between *SF*, the actual aircraft energy and a safe minimum energy.

4.3 Transient between airborne and ground phases; landings.

Currently, modern planes are equipped to perform NPA (Non Precision Approach) and Precision Approach.

In the NPA procedure a beacon which can be a VOR, an ADF or a Locator is placed in the axis of the QFU at a known distance from the threshold. Flying over it, at a requested height or altitude, the pilot engages a descent at a prescribed slope *with regard to the ground* at the correct heading. The difficulty lies in the knowledge of the wind. If the wind is known with an error of less than 6 to 8 kts, the descent could satify the condition (slope with regard to the ground) and the alignement with the runway requests a minimum vertical visibility of 120 m. If the wind is unknown or if the accuracy is less than 8 kts, the minimum vertical visibility should, at least, be 150 m

- for Precision Approach the only certified means is the ILS. The types of approaches are called CAT I (good visibility of the runway at a height of 60 m), CAT 2 (30 m) and CAT 3 (0 m). However for CAT 3 no airline operator has authorized their crews to land « 0-0 » (vertical visibility 0 m, horizontal visibility 0 m). A HD (Height of Decision) is

specified: this is the height (under the wheels) at which the pilot must see the runway (at least 3 high intensity lights, which are along the center of the runway) and check that it is on the axis within $\pm$ 2 m. If correct, then the landing and the breaking are performed automatically; if not, the pilot activates a « go around ». The HD depends on the aircraft equipment, the runway equipment and the crew qualification; for example, at Toulouse Blagnac airport, runway 15 R, for AirInter A-320, with a crew fully certified, the HD is 15 ft (under the wheels)

To comply with the second keyword « efficiency » it is necessary to generalize CAT-3 landings. There is a problem. ILS is installed in most of major european airports while it is installed on only 40 airports in US (fog is less frequent in US than in Europe). The frequency bandwidth just below the one reserved for ILS (boundary frequency 108.1 Mhz) is used by FM radioes. The power spectrum attributed to each frequency is specified: it is well known that they are not always respected and some complaints are collected every week by pilots reporting interferences between the ILS identification code and « private radioes ». Is it safe to go on a CAT 3 landing procedure when an interference is detected. Morever, the power allowed to each frequency for private radioes will no longer be limited starting January 1st, 1998 (France has decided to postpone this international recommandation to 2001).

The MLS (Microwave Landing System) is quite different from ILS though the objective are the same: CAT-2 landings. This system based on oscillating beams in the horizontal and vertical planes operates at 5 Ghz and, consequently, is less sensitive to jamming than ILS (108-112 Mhz). In addition it scans a $\pm$ 60° sector with regard to the axis of the runway and allows « curved approaches » while ILS implies an alignment some 10 nm in front of the runway threshold; in addition, to avoid interferences on the follower aircraft it is recommended that planes are always 5 nm a part. However, in spite of these attractive performances, the MLS will not be installed on the US territory according to a statement from FAA (1995). Europe is supposed to make a decision this year. The probability of a positive answer is low.

As we will see in parag.5, GNSS-1 (Global Navigation Satellite System) does not authorize landing CAT-3 (CAT-2 is right on the border of landing specifications).

It is mandatory to make a decision because the present rate of growth of Air Traffic raises the question: *will the airport be a limiting factor to the present rate of growth?*

Already now, in some airports the reduction of separations (from 5 nm to 3 nm) between planes in the final approach is considered. The reduction of separations points out the need to detect *the presence and to evaluate the intensity of wing vortices.*

The three major parameters attached to vortices are the energy of the vortex, its damping and its displacement; they are related to the aircraft (type, mass, configuration, position of center of mass) and to the position of the plane above the ground. There is an interaction between the two vortices which are created at the wing extremities: they go down and diverge a little. If they reach the ground, they bounce and diverge more. A second vortex, rotating in the opposite direction may be created by each main vortex. Fig 3 shows the evolution of vortices close to ground (from ONERA; numerical simulation).

If the vortices develop in a turbulent atmosphere, the evolution could be different: dislocation of the vortices with augmentation of the local turbulence.

In order to arrive at the minimum safe separation between planes it is mandatory to automatically *identify, detect the axis, evaluate the intensity and estimate the trajectoty* of the vortices. Sensors already exist (UHF and VHF Wind profilers, acoustic radars RASS, Doppler acoustic radars SODAR and conventionnal meteorological radars TDWR; Doppler lidars). Besides the ground detectors connected to high speed processor, on-board sensors are under study and experimentation. We can mention the european M-FLAME (Multifunction Future Laser, Atmospheric Measurement Equipement). The detection of vake vortices has been proved in flight using a Doppler lidar which acts as an anemometer. The objectives of the studies concern the extension of the possibilities:

-detection of windshears, of clear air turbulence, of dry hail, of the large scale mountain vortices and of the volcano ashes

-test of a pulsed 2 μm lidar for wake vortices and windshear.

-integration of the lidar into the on-board avionics in compliance with the certification requirements

Positively, though the main objective was, and still is, the reduction of separation in the approach phase, all the potentialities of new on-board equipment should be studied. This is why a large part of the study is devoted to the connexion to the FMS. New equipment intalled on-board will be accepted easily if some present equipment can be eliminated: the GNSS goes in this direction.

The concept of « autonomous sub-systems » has disappeared now. A modern aircraft is equipped with « distributed informatics »: parameters (static and dynamic pressures, total temperature, position of the mobile surfaces...) are picked up everywhere in the structure of the aircraft, they are partially processed, for example digitalized, and then fed on a bus (or buses). Processors pick up the data they need, and send the results either on a bus (IAS, TAS, static temperature, attitude...) or to actuators for control

surfaces. In addition, the temptation to re-use reliable software in new similar equipment may lead to catastrophies. The analysis of the accident of Ariane 501 (June 4th, 1996) is valuable. Below we give some comments extracted from the Inquiry Board Report [Ref 1].

The flight control system of Ariane 5 is of standard design. The attitude of the launcher and its movements in space are measured by an Inertial Reference System (SRI). It has its own internal computer, in which angles and velocities are calculated on the basis of information from a strap-down inertial platform (laser gyros and accelerometers). The data from the SRI are transmitted through the databus to the On Board Computer (OBC), which executes the flight program and controls the nozzles of the solid boosters and the Vulcain cryogenic engine, via servovalves and hydraulic actuators. There are two SRIs operating in parallel with identical hardware and software . One SRI is active and one is in « hot stand-by ». If the OBC detects that the active SRI has failed it immediately switches to the other one, provided that this unit is functionning properly. Likewise there are two OCBs. The design of Ariane 5 SRI is practically the same as the one used on Ariane 4.

The launcher started to disintegrate at about H_0+39 seconds because of high aerodynamic loads due to an angle of attack of more than 20 d° that led to trigger the self-destruct system launcher.

The high angle of attack was caused by full nozzle deflections of the solid boosters and the Vulcain engine. These nozzle defections were commanded by the OBC software on the basis of data transmitted by the active SRI (no 2). Part of these data at that time did not contain proper flight data, but showed a diagnostic bit pattern of the computer of the SRI-2, *which was interpreted as flight data.* The SRI-2 did not send correct attitude data because the unit had declared a failure due to a *sofware exception.* The OBC could not switch to the back up SRI-1 because that unit had already ceased to function during the previous data cycle (72 ms period) for the same reason as SRI 2.

The internal software exception was caused during execution of a data conversion from 64-bit floating point to 16-bit signed integer value. *The floating point number which was converted had a value greater than what could be represented by a 16-bit signed integer.* This resulted in an Operator Error. The data conversion instructions (in Ada code) were not protected from causing an Operator Error, although other conversion instructions of comparable variables in the same place in the code were protected. The error occured in a part of the software that only performs alignment of the strap-down inertial platform. *This software module computes meaningfull results only before lift-off.* Based on the Ariane 4 requirements, the alignment is operative for 50 s after starting of the Flight Mode of the SRIs. Then the operand error occured due to an unexpected high value of an internal alignment function called BH (Horizontal Bias) related to the horizontal velocity sensed by the platform. *The value of the BH was much higher than expected because the early part of the tarjectory of Ariane 5 differs from that of Ariane 4.*

This is why the final responsability for the design of the equipments in the aircraft could only be in the manufacturer's hands.

4.4 CFIT (Controlled Flight Into Terrain)

It concerns flights in which the crew was in good condition and no failure occured on board. There are about four accidents of that type per year.

It is clear that only automatic means, at least, for detection and evaluation of the risk of collision with the terrain and possibly for evasion, could lead to safety because the crew is unconscious of any danger.

For some 20 years GPWS (Ground Proximity Warning System) have been fitted on major commercial aircraft. A GPWS collects data from a radio-altimeter[1] which gives the minimum distance between the plane and the ground; it can be an inclined distance when the plane has a bank angle. The beam of the radio altimeter, which is tied to the fuselage may look to hills which are located on the sides of the prescribe route.

Such systems are becoming obsolete because there is no anticipation; when the alarm sounds, the collision with the ground is very probable even at the maximum load factor.

New systems are already being developped and tested. They are called MSAW (Minimum Safe Altitude Warning) or GCAS (Ground Collision Avoidance System). In the MSAW it is assumed that the aircraft is seen by a radar (at least one). From this position the height above the ground is computed and according to the instructions given by the controller to the crew, the sequence of heights within the next 30 s is derived. As soon as the height falls to the safe height an alarm is sent to the aircraft; when the distance to the ground along the trajectory reaches the minimum value for a safe recovery at the maximum safe load factor a « pull up, pull up » alarm is sent to the crew.

In the GCAS, the terrain profile around airports is stored in a large memory on board. The reference grid is the WGS-84. The usual mesh is 9''x12'' (about 230x280 m at 45° latitude). Ground altitudes are quoted with 4 digits. Military maps correspond to a 3''x 3'' (75x75 m) mesh. They are often in WGS-72; they are not all available.

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[1] a radio altimeter is not an on board radar looking at the ground; a frequency modulated signal is periodically sent toward the ground in a cone of about 40 d°) overture; the frequency of the maximum reflected signal is delayed by the transit time between the aircraft and the ground.

The Dassault/Sagem G-CAS privileges the extrapolation of the aircraft trajectory from the data collected on the GPS receiver, the baro-altitude and the radioaltimeter. The ground speed comes from GPS / INS. The actual maximum manoeuvers of the aircraft are also in the data base. The collision risk is derived from the evolution predictive model and the ground profile stored on board.

Thanks to the rapid development of earth ground profile data (Spot and other satellites) and the very high density achieved in memories (1 Go / 5cm^2) it soon will be possible to embark the earth profile on a 100 m x100 m mesh with a height precision better than 50 m. The anti collision with terrain will be automatic; it implies the determination of the escape trajectory on a precise route when this situation appears in a mountain area.

5 - EFFICIENCY

First let us say that most of the improvements which occured during the last 10 years, provide a better efficiency of the flights. However the large variety of electronic navigation aids (VOR, DME, ADF, DECCA, LORAN, OMEGA, ILS, GPS...) is a source of incidents or accidents if we compare it to what it would be (we can say, it will be) if there is a unique, worldwide, precise navigation means (GNSS).

5.1 Present deficiencies of GPS and GLONASS.

The main deficiency is the non *integrity* of these systems. Precision (S/A mode) is insufficient for landings. The worldwide cover is not provided 24 h / 24 for each individual system. The absence of an international agreement on the management of these systems leads to a strange ambiguity.

5.2 Near Future situation: WAAS, EGNOS, MTSAT

The lack of integrity may be compensated by permanent surveillance of satellites and information about failures to users through geostationary satellites. To do so, ground stations should be implemented. They should be interconnected; they can reset the satellite clocks and load the ephemerids. In addition the geostationary satellite can broadcast GPS time and ephemerid: it becomes an additionnal satellite.

This is in progress in US with the WAAS (Wide Area Augmantation System) with some 30 ground stations, in Europe with the EGNOS (European Geostationary Navigation Overlay System) and in Japan with MT-SAT.

Though no international agreement has sealed these programmes it is a first step towards cooperation. However, the key problem with these systems is the fact that satellites are controlled by military organisations of two countries.

5.3 ADS, ADS-B (Automatic Dependent Surveillance; B: Broadcast).

As mentionned previously, it has been agreeded to use the radar transponder either upon request (stimulation identical as the radar one) or periodically (the rate can be adjusted from half a second to 10 mn). Hence, in the B mode, identity of the plane, altitude or flight level, plus additional data which are not yet specified could be collected automatically. In flight experiments have prooved the validity and the value of the concept.

5.4 Medium term future (2005 - 2008): GNSS-2.

The present localisation systems will be turned off gradually. US authorities will turn off two Omega Stations in 1997. The programme EATCHIP / EATMS (European ATM System) forecasts the turn off of OMEGA in 2002, of VOR in 2005 and the up coming of GNSS-1 between 1999 and 2002 (GNSS-2 in 2015...) They also have decided to abandon ILS in 2003. ICAO will decide about the replacement of ILS by MLS in 1997 though the USA already decided that MLS will not be installed in the States....A confusing situation, to say at least!.

The GPS concept was finalized in 1973. Protocoles have not changed since that time. The volontary degration of signals (time and ephemerids) will no longer be acceptable in the future. The World Aeronautical Community is facing a strange problem. The only solution is to call for an *international management of a worldwide navigation system* . This will be the GNSS-2. Europe seems the most active in this future project. Propositions will be released next October. We can say that, obviously, it will be a civilian international project (satellites will not be protected against a nuclear flash and they will be much simpler than the present constellations; cost will be divided by 5), precision will be of the order of 10 m, landing CAT 3 will be possible with ground beacon(s) located on the airport

The automisation of the flight will be simplified and will lead to a higher level of safety if the integrity and safety of the unique positionning system are guaranted. The basic equipment will then be:

- INS, doubled with auto-check or tripled with voting device
- radar Mode-S transponder with a squitter (for the ADS-B mode)
- GNSS-2 receiver(s) associated with Differential signal processor

The data coming from the GNSS will be correlated with the INS data to give the best estimated position and velocity, namely during landings. They also will be connected to the G-CAS processor. The radioaltimeter could be used due to its simplicity. The flight processor (FMS) will be simpler than the present one but its safety and integrity must be proved at a level of 10^{-9}/h.

The last and very important problem to solve is the Cat 3 landing. It does not seem possible to assume it with the present system. Up graded D-GPS will satisfy the precision and integrity requirements for such landings. Systems based upon phase lock and ambiguity resolution on the carrier frequency of GPS (L_1 = 1.5 GHz) may lead to accuracy of the order of 1 cm. Some details will be given below about the localisation of mobiles on the airport plateform. Many experiments have been carried out with planes for precision landings; they all need ground beacons(s) called « pseudolites » (for pseudo satellites). Stanford University is working actively in this field.

6 - POLLUTION REDUCTION

The Air Transport System is criticized for acoustical and chemical pollution. In a report, dated Novembeer 8th, 1990, a working group on "Transportation" held by the EU/DG XII (LOTOS report) gave the pollution rate, expressed in g/km/pax, for TGV and aircraft. Electricity for TGV is supposed to come from coal or fuel for 100 % (not from nuclear energy).

	TGV	AIRCRAFT
CO_2	40	300
SO_2	0,01	0,2
NO_x	0,03	1,1 (4,4 g/s)
C_xH_y	0-0,002	0,2
CO	0,003	0,05
weighted figure for a 500 nm trip leads	0,5	2,5

In a study undertaken in 1973 by Aerospatiale, the possibility of moving the aircraft by hydraulic motors located in the landing gear and getting the energy from the APU was considered.

Assumptions: ground velocity 25 km/h slope of runways 3 %

Before take-off:

◆ ***without wheels motorization:***

- starting jet engine 3 mn

- APU: 5 kg
- engines: 60 kg

- ground movement 10 mn

- APU: 18 kg
- engines 169 kg

- duration 13 mn fuel consumed 252 kg

◆ ***with wheels motorization:***

- ground movement 9 mn:

- APU: 23 kg

- starting up the engine 3 mn

- APU: 3 kg
- engines 60 kg

- alignement 2 mn APU: 3 kg engine 34 kg

- duration 14 mn fuel consumed 125 kg

After landing:

◆ ***without wheels motorization:***

- duration 5 mn
  - APU: 9kg
  - engines: 84 kg

◆ ***with wheels motorization :***

- duration 5 mn
  - APU: 13 kg
  - engines 0

Balance additional mass: 237 kg

Fuel: -additional fuel due to the additional mass during the flight (500 nm)10 kg

- saved during the ground phases 205 kg
- saved during for a 500 nm flight 195 kg

Maintenance system cost was taken into account. The net results are :

- gain on DOC 0,65 %
- fuel saved per year (for a A 310) 350 t
- amortization: 1,5 year

It is surprising that nothing is suggested in this domain.

Hence, we will focus our comments on one subject: the *ground movements of planes -and other vehicles- on the airport plateform* because this subject concerns not only pollution but also *safety* and *efficiency*.

a) Nowadays, on some airports, ground movements are the limiting factor for landing/take-off rates. In bad meteo conditions planes may land in an automatic mode (CAT 3) at a rate of one landing per 120-150 seconds, a rate which is not acceptable for « driving » the plane from the exit of the runway to the gate.

b) Very often, a plane has to stop on the apron and wait for the freedom of the gate which is assigned to the flight; it can block other traffic ...

c) A 150 seat plane consumes 360 kg/h of fuel per jet engine when taxiing. A twin engine consumes 180 kg of fuel for each 15 mn taxiing or waiting. A diesel tractor needs about 15 kg to tow the plane from the gate to the threshold, holding and return included.

d) Due to the fact that the setting for the thrust is not (yet) controlled during the ground movements the thrust used corresponds to a maximum head wind and a maximum slope of the taxiway. Thus the pilot must use the brakes to adjust the speed. When the brakes (carbon type) are cold their degradation is extensive.

e) Noise during taixiing is not accounted for at the present time (below the prescribed threshold). However it is quite obvious that the ecologist pressure will react to this noise which are continuous all day long.

f) The jet engines deliver a high level of CO when taxiing, or holding (Fig.1). It would be a difficult problem to decrease the CO level when the jet engines are on « taxiing setting ».

Consequently, it is time to develop a means which will drive the plane as soon as it exits from

the runway, to the gate and from the gate to the runway threshold prior to take-off. The plane will no longer use its engines for taxiing. It could be the wheels motorization. It could be a tractor which should be automatized in the future. Then it is necessary to look for an automatic clutch between the plane and the tractor without stopping the plane. It is a difficult problem; once solved, the plane will be driven automatically from a control center with its jet engines stopped.

It is mandatory to control all vehicles on the apron either automatically or with electronic aids, if man-driven. During the first semester 1995 there were 150 « collisions » between vehicles and planes on the Orly platform.

The first problem to be solved is the precise positionning of all planes and vehicles on the platform. Some of the positionning systems listed below give also an instantaneous value of the speed (the speed vector obtained by derivation of the positions is not precise):

- radar for ground movements. Position is known at the control center and identity of the plane through the transponder. Guidance of the plane needs data transmission from the control center to the plane. The major problem concerns the masks due to buildings. No additionnal equipment on board requested.

- magnetic loops on the taxiways and on the apron in front of the terminal buildings. Localisation by the control center, no identity of the plane ; indication of the position on board with simple additional equipment. Magnetic loops can be identified. Experiments have been carried out on Toulouse-Blagnac airport.

- D-GPS tracking: position (and velocity) obtained on board ; could be transferred to the control center through an automatic data link.

- phase lock and ambiguity resolution on the carrier frequency L_1. If a reference position on the ground can be selected, the computation of the position of the « center of phase » of the antenna on the mobile does not request a large number of computations. If not, the relative position to a ground antenna reference is available but a large number of computations are necessary. In both cases the position of the reference point on the mobile lies between 1 dm and 1 cm. From these positions the trajectory of the reference point can be determined with accuracy. Identification may be collected through ADS-B

The second problem is to compute the present occupied volume, to extrapolate the trajectory and to compute the volume which will be swept during a prediction time (10 s for example). To do so it is necessary to assume that the automatic control system of the vehicle or the driver assisted by electronic aids for guidance does not follow exactly the guidance law. The predicted volume is in fact much wider that the one which will be occupied. It should be graduated in probability; no « predicted volume » must be in contact in the "0,999" contour.

The european project DAFUSA (Data Fusion for Airprts) concerns the collection of data from various sensors on the airport and the validation of data prior to their injection into a data base. The objectives are the detection, the identification, the prediction of conflicts and their resolution. The sensors include Mode-S signals, GPS, D-GPS, D-VHF and primary radar data.

The third problem concerns the guidance laws which allows the safe guidance of the mobile and the final positionning (about 1 dm) for tractors attached to a plane

Mathematical solutions exist for an articulated vehicle even if it goes way back. The use of a neuronal network for driving the tractor in such a way that the trailer be aligned at a precise position provides good solution after the necessary training period by a driver. Recently, mathematical solutions (« flat systems ») have proved their validity in the case of a tractor to which is attached *two* trailers (an approach to the train of trucks for luggage conveyance).

The automatic circulation of planes on the airport plateform is a difficult problem, but the issue would double virtually the number of gates in the terminals: as soon as the last passenger has disembarked, the plane could be pushed back to a location on which it can be cleaned, refuelled and catered. It will be tracked to a gate just prior to the embarkment.

As to the chemical pollution, it is worthwhile noting that the present ejection of CO and NO_x is ten times less than it was 20 years ago in the cruise phase. Attention is placed on the other phases of the flight including the ground movements as stated above.

Going back to noise in the approach phase, curved approaches with D-GPS (or GLONASS) is a solution. The curve approach can be used to dilute the noise effects over a large area and avoid the concentration of planes on the axis of the runways; it also permits to shorten the approach path for planes coming from the opposite direction of the QFU. During these phases hard coupling between the GPS receiver and the INS is mandatory namely if CAT 2 landings are performed. [Ref 3]

7 - SYNTHESIS AND CONCLUSIONS

Today, planes are nearly fully automatized. If there is no interference with other planes in the sky a commercial flight can be performed automatically except for the acceleration on the runway and the rotation. Once the plane has reached the correct attitude for initial climb the pilot may engage subsequent phases by pressing the adequat button (IAS, vertical speed or attitude; reach such altitude, take such heading or follow such route which is stored in the FMS; idem for the descent: go to such fix, capture ILS, make Cat 3 landing...). The

pilot may also engage after take-off the vertical and horizontal profile of the route to destination which is stored in the FMS (or FMGC). But normally interference with other traffic occurs and the initial flight plan stored in the FMS; is modified by the control. Pilots may control the plane through the automatic sub systems in accordance with the instructions given by the control or he can modify the data stored on board to comply with the instruction. Ambiguity may rise through the T-CAS; if the alarm is activated, the pilot reacts accordingly, whatever the instruction of the control be.

The automization of the acceleration and rotation would be difficult to monitor for many reasons. However the automatized flight as described above is tied to corrrect adjusment of the frequencies of the beacons which are used during the flight. Morever, the precision of localisation of the plane varies according to the type of beacon used during the flight. Ground radar position data is not received on board.

The introduction of automatic data transmissions, both ways, will improve the safety level of the flight: data sent by a controller (for example, an instruction which modify the flight level) will be displaid on board; if the pilot accepts the instruction, he transfers it to the FMS or to the automatic pilot by pushing a button; instructions are sent back to the ground and checked for correctness. The ADS (common mode, i.e. query from the ground) will send high value data picked up on board, for example, bank angle, indicating the rate of turn of the plane or, at least, data (2 digits) indicating if the plane is turning right or left. Such data will improve the prediction of trajectories by the controllers

The arrival of a unique world wide positionning system (GNSS-1), will simplify the type of operations which are carried out on board and consequently increase the safety of the flight. The position accuracies of all the planes flying in a given vicinity will be the same. At least Cat 2 landings could be achieved with the GNSS-1.

Due to the ADS-B positions of planes flying in the vicinity of another plane will be known by the latter on a permanent basis without any request from the pilot.

To take into account all these potentialities, Boeing and Airbus have decided to enlarge the capabilities of the FMS. For Airbus the new FMS, which will be delivered starting June 1998, will include the processing of the GPS / GLONASS data and the monitoring of the automatic data transmission between the ATC and the crew; this is the ATSU (developped by Aerospatial). Data concerning the approach and departure regulation on most world wide airports, which are renewed every 28 days, will gradually include data concerning GPS approach, namely curved approaches (at least one airport is already certified by FAA for curved approaches -Juneau, Alaska). The exchange of data between the FMS and the electronic card which controls the automatic pilot and the power setting (FADEC: Full Automatic Digital Electronic Control) will include the automatic protection of the flight envelope. This new FMS will be able to automatically control the descent in order to arrive at a given point, threshold of the runway for example, at a precise time (better than 10 seconds) set up at the begining of the descent; errors on wind estimations will be compensated, real time during the descent.

Then, can we say that around 2000 quasi-fully automatic flight up to landings CAT 1 would be possible?

However, the on-board data processing should be carefully checked; it is quite impossible to simulate all the possibilities which may happened during the flights. Abnormal situations may appear though no failure are present on board (Ariane 501 accident). A temporary degraded state, allowing some time for deeper investigations, could be a recommended solution for the present time.

The role of automation is clear, the « free flight concept » will be a good solution to solve air traffic growth. For the en-route phase, in the near future, it can be assumed that « free flight » will concern flights with a « flight plan » which do not necessarily use the routes registered on the maps, but registered before the flight; an agreement between the ATM and the Captain will be mandatory The major problems which are without a solution at the present time concern the airport saturation around 2005- 2010. A global approach to the problem is mandatory. For example, it will point out the necessity of automatizing the ground movements of all mobiles on the plateform or to arrive at a unique quasi-real time wind data base on the airport, accessible by pilots and controllers in an automatic way.

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EMERGING MILITARY UNMANNED AIR VEHICLE SYSTEM CONCEPTS

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SUMMARY

Unmanned Air Vehicle (UAV) systems are evolving with unprecedented mission area capabilities. Next generation military UAV's offer the potential for achieving a revolutionary reduction in the total cost of conducting tactical air warfare. Exploiting the full potential of UAV's in terms of overall cost and mission capability is highly dependent on the ability to safely operate quasi-autonomously in a dynamic multi-vehicle combat environment. Continuous remotely piloted techniques and fixed pre-determined way point flight trajectory systems of the past, are giving way to more highly automated vehicle management systems to provide variable autonomy consistent with mission needs, overall system integrity and user confidence. Development of multi-dimensional guidance and control, adaptive agent based flight management and information fusion technologies represent the essential enabling elements to permit safe and effective operational employment of unmanned strike aircraft. As the military community develops and matures the UAV technology base, commercial spin-off applications are also beginning to emerge, e.g. law enforcement, ground traffic surveillance, maritime patrols, and wide area telecommunication. The combined commercial and military UAV application trend will have serious implications with respect to civil airspace usage and associated vehicle certification requirements and standards.

INTRODUCTION

Historical Perspective

Emergence of reusable unmanned military vehicles dates back to the 1950's. The NATO military community has employed unmanned systems for the past several years, to achieve stand-off engagement advantages over an opposing adversary for a variety of mission functions, including reconnaissance, surveillance and lethal strike. For definition purposes, unmanned military flight vehicles can be classed into two general categories: a.) non-returnable powered "launch and leave" weapon systems, e. g., cruise missiles, "flying bombs", etc. and b.) reusable Unmanned Air Vehicles (UAV). This paper concentrates on the evolution and implications of UAV systems in the context of air traffic management decision aiding, automation and flight path optimization considerations.

Serious UAV concepts, such as the Teledyne Ryan AQM-34 began to emerge in the early 1960's. This type of vehicle began to distinguish its predecessor "flying bomb" unmanned systems, by introducing autonomous internal guidance and more system functionality. Historical examples of unmanned combat system applications are highlighted in Figure 1.

Historical Perspective - Unmanned Military Vehicle ons

Time Frame	Theater of Operation	System Concept	Military Functions
1950 - Current	Peacetime Training	Numerous	Surv/Decoy/ Recce/E-W
Late 1960s	Vietnam	Firebee	Recce, E-W Decoy
1982	Beka Valley	Samson	Defense Suppression Decoy
1991-93	Iraq	Cruise Missile	Lethal Strike
1996-97	Bosnia	Predator	Recce/Surveillance

Figure 1 - Historical Perspective

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Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

Early application of military unmanned systems was limited primarily by technological capabilities as opposed to military operational acceptance of unmanned elements. For example over 3400 combat reconnaissance missions were flown using the Firebee series UAV during the Vietnam era conflict. Clearly, the UAV concept of operation was successfully employed in a limited recce role, for which no other system alternatives could provide the same level of cost effectiveness, within the required mission parameters of survivability, area coverage and time criticality, resolution etc. Today, for these same reasons, the Predator UAV is used extensively in Bosnia as the vehicle of choice for surveillance missions.

In times of war, necessity is often times the "mother of invention". The Israeli's are widely reported to have successfully employed UAV's during a 1982 raid to carry out highly effective diversionary tactics and surveillance functions in connection with defense suppression missions. While these and many other noteworthy examples clearly attest the emergence of militarily viable UAV systems, they were inherently limited in their mission utility. These limitations are attributed to a general lack of real time adaptability and reliable automated control for mission applications, involving precise time critical positioning under fluid battlefield situations.

Technological Trends

Over the past 25 years, UAV capabilities have evolved with unprecedented capabilities, as a result of unrelenting NATO investments in critical technologies, such as vehicle optimization, guidance and control techniques, computers, information processing, communications, and remote sensing. Today military UAV's are on the threshold of yet another significant revolution, as these technologies are further developed and refined to permit more "manned aircraft like" attributes at a fraction of the total cost of manned weapons systems. The underlying core technology trends are highlighted in Figure 2.

Several recent studies, notably the USAF New World Vistas and the NATO AGARD Aerospace 2020 technology forecast assessments, have consistently highlighted the ever expanding role of UAV's in virtually all traditional military mission functions, such as reconnaissance, surveillance, lethal strike and battle damage assessment. Figure 3 depicts the emergence of UAV sophistication using a relative Figure of Merit (FOM), which represents composite UAV capability in terms of basic vehicle attributes, on-board mission systems and overall mission utility. The message is clear; UAV systems are rapidly taking on mission functions, which have historically been assigned to manned aircraft weapon systems.

Military Implications

One of the central issues facing the NATO military community is affordability of aerospace systems. Future requirements will likely be driven by diverse military capability needs, rather than explicit monolithic threat based scenarios. The rapidly expanding technology base coupled with sharply declining defense budgets, has forced senior military planners and system developers to seriously re-examine future military mission area needs, in light of the projected potential of unmanned systems.

The aforementioned AGARD study projects fundamentally new weapon system concepts centered around a class of unmanned tactical aircraft (UTA). Vehicle size and performance capability are envisioned to range from a micro vehicle (2 to 20 Kg) size to hypersonic vehicles and ultimately to conventional tactical fighter size vehicles, with virtually all of the manned attributes without accompanying penalties.

The UTA concept offers significant potential for achieving a revolutionary reduction in the total cost (acquisition, O & M and human life) of conducting tactical air warfare across the full mission area spectrum, e.g., peacekeeping, interdiction, RTSA, etc. This reduction arises from the realization of several key UTA attributes:

GUIDANCE, CONTROL, & AVIONICS TECHNOLOGY IMPACT

	1960	TODAY	2020
COMPUTING POWER • Solid State Electronics • Optical Computing • SSI, LSI, VLSI • Protein Based Computing	KIPS	MIPS	BIPS
SENSOR DETECTION/RESOLUTION • Scanned/Staring Arrays • Electronically Steered Ant. • Ring Laser Gyro (RLG) • Fiber Optic Gyro (FOG)	< 1 KM 15 Milliradians	< 5 KM 0.5 Milliradians	< 50 KM 0.01 Milliradians
ALGORITHMIC/SYMBOLIC METHODS • Classical State Space • Fuzzy Logic/Neural Nets • Soft Computing • Artificial Intelligence	Single Loop Optimization	Multi-Loop System Optimization	Overall Mission Loop Optimization
MODELING & SIMULATION • Super Computers • 3D Visualization • CAD • Multi-Media	Stand Alone Vehicle and Subsystems	Integrated System	Virtual Reality Environment
NAVIGATION ACCURACY • Inertial Navigators • Digital Terrain Mapping • Satellite Navigation • 4-D Navigation	1000 m/Hour	100 m/Hour	1-10 m/Hour
FLIGHT PATH STABILIZATION • Fly-by-Wire Technology • Relaxed Static Stability • Multi-Variable Control • Control Configured Vehicle	Statically Stable	Variable Stability	Configuration Tailoring
VEHICLE MANAGEMENT ARCHITECTURE • Optical Air Data • Photonic Interfaces • Distributed Processing • Fault Tolerance/Reconfig	Pilot Centered	Automated Subsystems Control	Real-Time Integrated Performance Optimization
REAL TIME ON-BOARD MISSION FUNCTIONS • Information Fusion • Knowledge Based System • Artificial Intelligence • Digital Processing	Autopilot Functions	Integrated Flight/Fire Control	Integrated Multi-Ship Mission Package

Figure 2 - Core Technology Trends

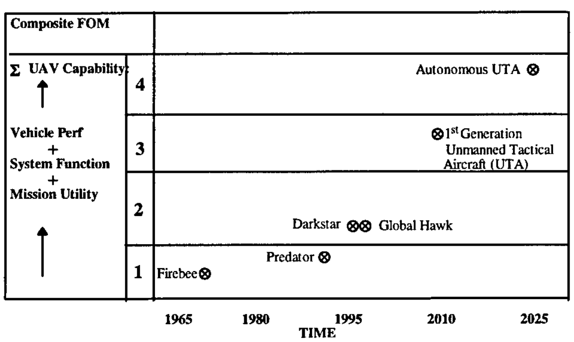

Figure 3- UAV Capability Trend

- Reduced peace-time training and support infrastructure
- Increased stand-off precision engagement capability
- Missionized vehicle modularity and storage
- Long endurance / rapid response
- Extended long range / endurance capability
- Automated decision aiding for rapid reaction

Achieving the full military potential of UTA's is highly dependent upon resolving numerous crucial acquisition and employment issues. For example, interoperable system assets must be consistent with multi-national mission objectives. System attributes and requirements need to be optimized across multiple mission capabilities and cost constraints. With respect to operational employment, there are further serious implications associated with UTA:

- Concepts of operation
- Infrastructure (maintenance, basing, training, etc.)
- Terminal area ops and airspace management involving mixed manned and unmanned vehicles
- Degree of autonomy with respect to mission management, command and control functions
- Force mix balance
  - Manned vs. unmanned
  - Specialized vs. multi role assets

Enabling UAV Technologies

On the technology side, investment in the development of the several key technologies is essential for continued evolution of expanded UTA mission capabilities.

- Integrated vehicle configuration tailoring
- Multi dimensional control optimization techniques

- Agent based adaptive guidance and control
- Automation and decision aiding methods
- System wide integrity management
- Vehicle / flight management systems
- Man machine interaction
- Information fusion and distribution
- Secure data link communication
- Long term storage systems
- Multi spectral sensors
- Micro mechanical & E-O devices

UAV STATE-OF-THE-ART

Representative Current Systems

Predator (Tier II): The Predator (Tier II) is a relatively low speed (75 -110 knots) medium altitude endurance (25000 ft) UAV manufactured by General Atomics Aeronautical Systems. Designed for 40+ hours endurance missions at 500 mile range from the launch and recovery zone, Predator carries a 450 pound payload, which includes an electro-optical (E-O) and infrared (IR) sensor package or a synthetic aperture radar. The Predator vehicle also has the capability to collect video imagery and transmit near real-time via satellite or line of sight data link. Predator has been used extensively in Bosnia for reconnaissance and surveillance missions.

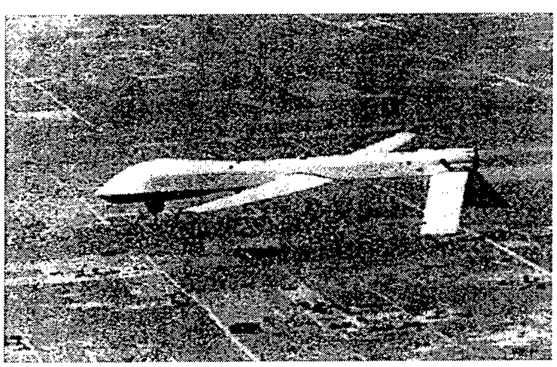

Figure 4 - Predator UAV

DarkStar (Tier III Minus): The Tier III Minus DarkStar Unmanned Aerial Vehicle completed its first successful flight 29 March 1997. Manufactured by Lockheed Martin in Palmdale, Calif., and Boeing Defense and Space Group in Seattle, Wash., DarkStar has a short, disk-shaped body and 69-foot wingspan. With its wings off, it can be carried aboard a C-130 transport. DarkStar is a high-altitude, high-endurance UAV optimized for reconnaissance in highly defended areas. Planned for operation within the current military force structure, and with existing command, control, communications, computer and intelligence equipment, DarkStar is capable of operating at a range of 500 nautical miles at altitudes up to 45,000 feet, while loitering over a target area for more that eight hours with either electro-optical or synthetic aperture radar sensor payload.

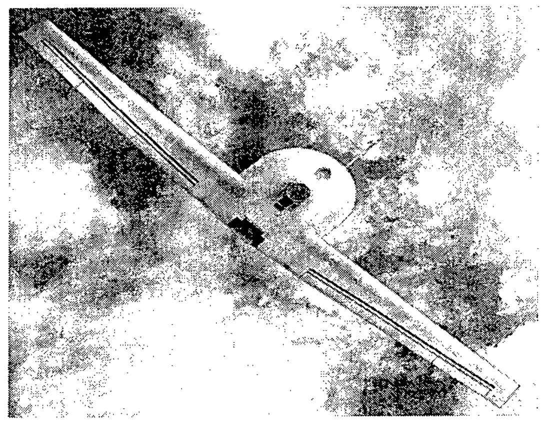

Figure 5 - DarkStar UAV

Global Hawk (Tier II Plus): On Feb 21, 1997 a new chapter in reconnaissance history began with rollout of the Tier II Plus Global Hawk Unmanned Aerial Vehicle at Teledyne Ryan Aeronautical in San Diego, Calif. Global Hawk joins its sister UAV, the Tier III Minus DarkStar, as part of a family of uninhabited, aerial reconnaissance vehicles under development by the U.S. Department of Defense. Global Hawk is a high-altitude, long endurance UAV that will relay near-real-time imagery day or night, in good weather or bad, at one-foot resolution over geographic areas of approximately 50,000 square miles. Capable of traveling up to 40 hours and 14,000 nautical miles from its Main Operating Base (MOB), Global Hawk will be able to remain on station at 65,000 feet over a forward target area 3,000 miles away for more than 22 hours. Returning to the target area, it can then remain on station up to 31 hours at a time before heading back to the Forward Operating Base. With a

wingspan of 116 feet and total weight of 25,600 pounds, the 44.4-foot-long craft can carry payloads up to 2,000 pounds, cruise at 340 knots above 60,000 feet, and operate from conventional 5,000 foot runways. Once deployed, Global Hawk can be programmed to take off and land automatically by the Launch and Recovery Element (LRE) of a companion, manned ground segment, located at the FOB and equipped with a Differential Global Positioning System (GPS). Once Global Hawk is airborne, commanders located on the ground will be able to select radar, infrared and visible wavelength reconnaissance modes, and use the SAR / MTI simultaneously with either of the other two sensors. Potential threats to Global Hawk will be detected through an Air Force Mission Support System-based, automated mission planning system, and the vehicle's flight profile will be automatically adjusted to avoid threats. Future plans for the new UAV include working in concert with Advanced Warning and Control System (AWACS) aircraft and the Joint Strategic Tactical Airborne Reconnaissance System (JSTARS). Allowing ground-based operators to monitor and operate the air vehicle and its sensor suite at all times almost anywhere in the world, Global Hawk's communications system will feature multiple satellite and line-of-sight data links for mission control, launch and recovery elements of the ground segment. Wide-band data links will help Global Hawk transmit large amounts of data to the mission control element, which can be located thousands of miles from the aircraft's operating area. Global Hawk will offer battlefield commanders unequaled situational awareness in future armed conflicts.

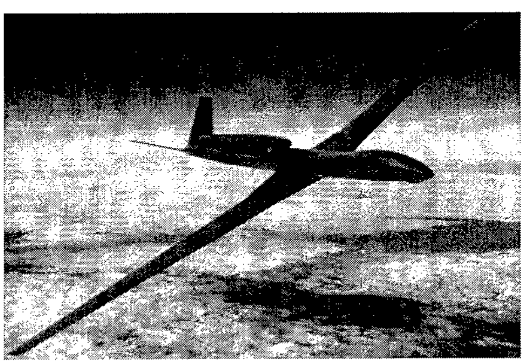

Figure 6 - Global Hawk

Future Concept

Unmanned Tactical Aircraft (UTA): The term Unmanned Tactical Aircraft (UTA) (also referenced as Uninhabited Combat Air Vehicle (UCAV)) embodies the next generation of military UAV concepts, based on current technology trends and future projection. The concept reflects integration of several key technologies into a complete tactical airpower system to enable a general purpose high performance aircraft to perform a full range of lethal missions, without the physical presence of a pilot in the aircraft, at a fraction of today's tactical aircraft cost.

The UTA concept encompasses a broad class of recoverable vehicles designed to conduct the full range of tactical missions using ordinary aircraft weapons, onboard sensors and tactics. UTAs will exploit the many sources of off-board information available in the modern theater of operations. Flexible off-board control of the air vehicle places the operator at the center of the information architecture, whether the control station is ground, air, or sea-based. This will allow the operator to exploit information from on-board sensors, off-board reconnaissance and surveillance sensors, and theater databases of information from all sources. The UTA concept is envisioned to support a range of missions of increasing complexity from reconnaissance, at the low end of complexity, to air-to-air combat, at the high end. At the highest levels of complexity and capability, human operator intervention is essential. Although the UTA is uninhabited, it is capable of functioning in much the same fashion as a piloted vehicle; thereby enabling a remote operator to use the full range of human judgment, intellectual capabilities and moral authority. Human interaction is the key, which will allow UTA's to operate as flexibly and effectively as manned aircraft. UTA's will be capable of operating from ordinary airfields and fly in controlled national airspace with varying degrees of operational autonomy, dictated by mission requirements and inherent system limitations.. They will conduct missions in peacetime situations, in crisis situations and in wartime. UTA operators will be able to observe rules of

engagement and make the critical decisions to use or refrain from using force and operate in uncertain and confusing situations. For less complex missions, such as reconnaissance, fully autonomous aircraft are already a reality. For the more complex missions, the objective is to automate all but the highest level decision making processes which require human judgment.

The UTA control architecture necessitates a modular design to allow multiple control options for operational flexibility. The location of the control station (ground, air, or ship-based) and the degree of autonomy between the station and the air vehicle will be variable to facilitate a general tactical air vehicle which can be adapted to accomplish a full range of missions. Variable autonomy and allocations of tasks will allow each control station to control more than one UTA, since the operator only has to focus on high level mission functions. An appreciation of the state transitions which will characterize UTA operations is shown in Figure 7 below. UTA operational state diversity has significant ramifications on control system technology requirements, because of the different environments in which the system must function, ranging from runway operations and operations in controlled national airspace through full combat operations. Each control function and the technologies which support its accomplishment must have the flexibility to adapt to these changing environments.

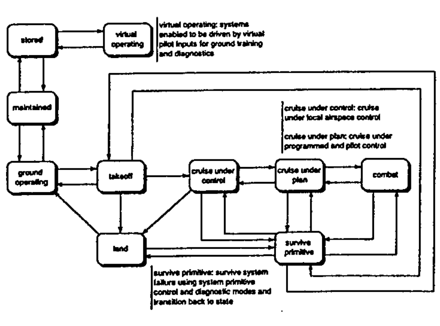

Figure 7 - State Transitions for a UTA System

KEY TECHNOLOGY CHALLENGES

Flight Management and Control

Exploiting the full potential of Uninhabited Combat Air Vehicles (UCAV's), in terms of overall cost and mission capability is highly dependent on the ability to safely operate quasi-autonomously in a dynamic multi-vehicle combat environment. Continuous remotely piloted techniques and fixed pre-determined way point flight trajectory systems of the past, are giving way to more highly automated vehicle management systems to provide variable autonomy consistent with mission needs, overall system integrity and user confidence. Realizing effective and practical military UAV weapon systems, centers around the development of viable technology approaches to the basic flight control problem as illustrated in Figure 8.

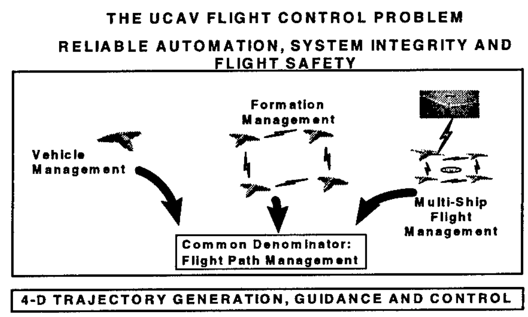

Figure 8 - The UCAV Flight Control Problem

Multi-Vehicle Integrated Control System Approach

Multi-ship integrated control technologies are essential for internetting multiple platforms, manned or unmanned. The cooperative employment of multiple platforms enhances situation awareness, survivability and mission effectiveness. A highly integrated multi-ship control system allows teams of manned and unmanned strike aircraft to enter combat under the management of an "On-the-Scene" fighter pilot/crew member or airborne mission controller. This concept embodies the control strategy for a composite multi-ship flight management system that will automate and integrate on-board planning and control functions. It integrates flight control, integrity management, flight and mission management technologies with advanced processing and communications systems that can be employed in a variety of military missions and theaters of operation. The core flight control

technologies depicted in Figure 9, represent the essential enabling elements to permit safe and effective operational employment of unmanned strike aircraft.

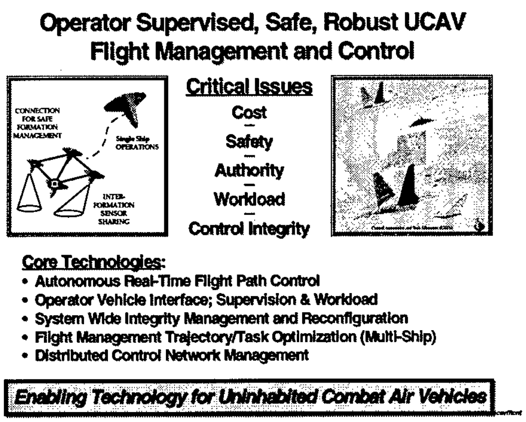

Figure 9 - Core Flight Control Technologies

A combat strike package could comprise a composite set of manned and unmanned lethal vehicles, or a composite set of all manned or unmanned vehicles. A fully integrated vehicle flight management system would provide significant advantages to the warfighter, through the automation of flight control and mission functions including, cooperative flight path management, trajectory generation, re-planning, rerouting, as outlined in the integrated system architecture of Figure 10.

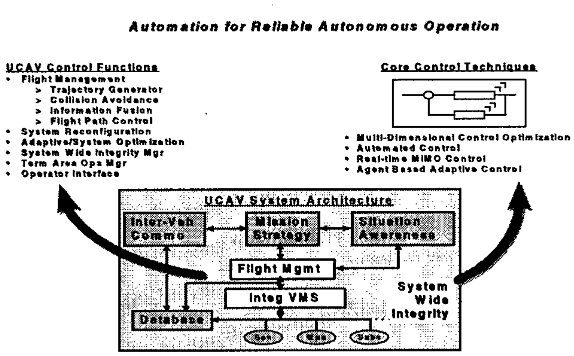

Figure 10 - UCAV Integrated Flight Control System

Development of credible automated control techniques and autonomous decision making algorithms, along with the means for assuring compliance with operational doctrine, mission objectives and constraints represent the essential central focus in achieving versatile UCAV's. Specifically, the UCAV integrated flight control/flight management system should embody the following important features and capabilities:

(1) At least fail-safe integrated control system implementation; system wide integrity management, automated fault tolerance, package reconfiguration strategies, and graceful degradation techniques, e.g., degradation of link, loss of link, loss of leader; dispersed and cooperative control architectures; appropriate self-health monitoring for the multi-vehicle force package health assessment, assets availability, and communication

(2) Effective response to remote operator authority;

(3) Basic autonomous operations; terminal area (take-off, land, ground ops), fly to/hold orbit, refueling, execution of pre-selected tactics with appropriate response to unplanned events and emergencies; automated collision avoidance, formation control and dynamic deconfliction;

(4) Variable levels of system autonomy/interaction and transition from remote pilot control to semi-autonomous control and operation in a fully autonomous mode; multi-ship flight path management and cooperative trajectory generation algorithms; advanced optimization techniques and adaptive control algorithms, e.g., fuzzy logic, neural nets, genetic algorithms, and knowledge based systems; real-time automated multi-vehicle task allocation, tactics, doctrinal constraints, cooperative planning and distributed decision making algorithms;

(5) Acceptable user workload; management and supervision;

(6) Beyond LOS control, situation awareness, adaptive response and status information feedback;

(7) Consistent track/shared data coordinate system transformations for accurate presentation of information, situation awareness and operational safety parameters; information fusion and transfer via secure/anti-jam communication; enhanced situation assessment using machine perception, synthetic vision and virtual reality techniques

Autonomous Multidimensional Control Techniques

The central notion of system autonomy is intimately connected with advances in information and control technology. An autonomous system must be designed with the capability to generate goal directed behavior patterns relative to uncertain real world dynamic environments. Goal directed behavior in autonomous systems is achieved through closed loop feedback control. Interaction of the autonomous system within its environment can be decomposed into the following essential feedback functions: monitoring, diagnosis, plan generation, selection and execution. Automation of these feedback elements requires a system implementation based on learning, problem solving, inferencing, decision making and conflict resolution. In the case of unmanned autonomous systems, information processing and control algorithms must be developed using knowledge based machine intelligence techniques to effectively perform the required feedback functions. Because of the tremendous real world complexities and uncertainties, traditional top down hierarchical computational methods must be complimented with a behavior oriented architecture, in order to solve the multi-dimensional autonomous task control problem.

The resulting goal directed structure provides the appropriate paradigm for self organized learning and globally optimized adaptive agent based cooperative performance, relative to ever-changing real world situations. Cooperative knowledge based agents represent the classical "manned" aircraft piloting functions, such as, sensor fusion, situation assessment, route planning, trajectory generation and flight path management, etc. Realization of robust adaptive agent based autonomous systems over the next 20-25 years, is predicated on continued development and application of new computing methodologies, such as, neural networks, fuzzy logic and genetic algorithms in concert with projected increases in computer processing power.

AIR TRAFFIC MANAGEMENT IMPLICATIONS

As the military community develops and matures the UAV technology base, commercial spin-off applications are also beginning to emerge, e.g. law enforcement, ground traffic surveillance, maritime patrols, and wide area telecommunication. The combined commercial and military UAV application trend will have serious implications with respect to civil airspace usage and associated vehicle certification requirements and standards. Specific issues are highlighted below:

Enroute Flight Path Management

- Maximum number of vehicles operating in congested sectors with respect to mixed manned and unmanned vehicle operations
- Minimum safe separation requirements
- Dedicated data link vs interactive voice communication requirements
- Command and control response verification
- Human oversight and intervention methods

Terminal Area Operations

- Extent of on board UAV functional capabilities, such as: computer vision, voice recognition, 4-D auto route trajectory generator, and deconfliction algorithms

- Recovery techniques: autonomous UAV approach and landing vs continuous man in the loop control
- Safety considerations with respect to inherent vehicle reliability and system wide integrity

Safety considerations will obviously limit the introduction of UAV's along very conservative lines. However, as key UAV technologies mature, one can expect increased levels of reliable system automation and credible autonomous operation to the point, where UAV operations could become transparent to the civil airspace infrastructure.

CONCLUSION

Emergence of sophisticated unmanned military vehicle concepts is evolving at accelerated pace. Current military needs have spawned a new era in the development of versatile UAV systems. Highly innovative configurations and system capabilities are opening the door to broader mission area applications. Projected technology advances in information processing and control techniques are expected to result in unprecedented levels of reliable automation and safe autonomous operation. Senior military leaders are beginning to seriously plan for the long term introduction of next generation UAV systems in the inventory and operational infrastructure. Commercial applications are also emerging, with attendant implications on civil airspace and associated certification requirements and standards.

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ATM as Part of the Aerospace Engineering Curriculum

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ABSTRACT

The problems of changing the traditional aerospace engineering curriculum to provide an education for young engineers interested in developing the new forms of ATM systems is discussed. The new ATM systems will introduce quite different concepts for operational procedures and a much higher level of traffic handling performance using new technologies for Communications, Navigation, and Surveillance identified by the FANS Committee of ICAO, and will introduce digital datalink and automated d[1] ecisioin support processes in the cockpit and at the ATC sontroller's console. It is concluded that subjects in Human Factors and Operations Research pertinent to ATM operations are badly needed, and that there is not enough time in the normal curriculum to teach all necessary subjects for a completely qualidied ATM Project engineer so that short courses are needed for engineers from industry to prepare them for this responsibility.

INTRODUCTION

The recent increased interest in the development of new forms of Global Automated ATM Systems (GATS) based on recent advances in CNS technologies raises various issues in the education of young engineers capable of designing, testing and implementing such systems over the next 25 years. To introduce a global system which has new concepts for ATM operations which allow a higher level of traffic handling performance, and which introduce automated digital communications and human centered automation for decisionmaking both in the cockpit and on the ground engenders quite different tasks from the traditional problems over the past 50 years. These problems were much simple and much smaller concerning only the introduction of incremental improvements to various components of the existing manual ATM systems (such as primary and secondary radar, radar displays, voice communications between air and ground elements, various ground-based radionavigation aids, landing aids, etc.)

The undergraduate and graduate curriculum of aerospace engineering departments in the western world has always reacted to the changing needs of the civil and military markets for both aeronautical and space activities, and is ideally situated to make curriculum changes which will supply young engineers who can meet the requirements of the new tasks for development of GATS.

TODAY'S AEROSPACE CURRICULUM

The multi-disciplinary curriculum of aerospace engineering departments today can usually be described in the following generalized manner:

For the undergraduate education;

1. basic courses in mathematics, physics, and science
2. technology courses which introduce the four aerospace techologies essential to the engineering of aerospace vehicles, namely;
   - Aerodynamics,
   - Propulsion,
   - Structures and Materials, and
   - Guidance and Control

For the graduate education;

a diversified set of advanced courses in one of the technology areas supplemented by advanced courses in mathematics, physics, and science, all of which are tailored to be pertinent to student thesis research activities of an experimental or theoretical nature. Most aerospace engineers complete at least the Master's degree level, either before or after employment in the aerospace industry.

Current trends - Undergraduate

Some aerospace engineering departments have been making changes in the traditional subjects by adding computer science courses and basic telecommunication courses to the

[1] Paper presented at the NATO AGARD Mission Support Panel Workshop in Air Traffic Control, 27-29 May 1997, Budapest, Hungary

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

undergraduate curriculum. This reflects the growing importance of the applications of computers and digital datalinks in the overall design of aerospace vehicles.

Current trends - Graduate

In the graduate education, departments have been adding courses and research activities in Human Factors and Automation, and developing programs which are designed to educate "systems engineers" to lead the multidisciplinary teams which develop modern aeronautical and space vehicles. Both of these activities are pertinent to educating the type of engineer needed to lead the engineering teams which develop the new GATS.

ENGINEERING OF ATM SYTEMS

Let me remind everyone of the definition of engineering:

> "**Professional Engineering** is the art of applying validated Technologies to real world problems in a manner which is cost effective, aesthetic, and environmentally acceptable"

Although calling themselves "engineers" many never get the chance to practice the profession of engineering as defined above. Persons trained in Science and Technology can participate in three different types of highly interrelated activities after graduation:

1. Research,
2. Technology Development, and
3. Engineering.

Let me distinguish between these three different types of activities to make clear their interrelationships since there is a need to educate persons for all three types of activities to accomplish a good practice of ATM engineering.

"**Research** is the activity of collecting and organizing existing technological knowledge in some area, and then creating new knowledge".

"Scientists", or "Research Engineers" are highly trained in some area of science and technology and interact with other scientists/researchers and technologists. They do not deliver real world systems to customers. They deliver research results to Technologists.

"**Technology Development** is the activity which uses existing knowledge and technology to create a prototype which validates an extension or improvement the performance of a given technology product."

"Technology Development Engineers" or "Technologists" engage in the development, testing and validation of new technologies which have been created by Researchers. They interact with Researchers on one hand and Professional Engineers on the other.

Using the previous definition of Professional Engineering, I can now define the "**Professional Engineer**" as a person who delivers the benefits of a new technology to some "end-use" customer who is not trained in science and technology but who has a real world application for the products of the new technology and considers the price of the new product to be reasonable in terms of its improved performance. Engineers interact with Technologists on the one hand, and customers with dollars on the other. They must be broadly skilled in many disciplinary areas of technology, but also knowledgeable in areas of finance, political science, environmental science, law, economics, probablility and statistics, reliability and safety, manufacturability, and maintenance, real world operations and human factors in the area of application, interpersonal skills in dealing with a team of engineers and the customers (who also may be a diverse team of people with different value sets), etc.

Professional Engineers are not developed by universities - it takes several years of industrial experience in a learning environment to create a qualified Professonal Engineer. Universities can only start a person on the career track which creates a person with such a formidable array of skills by making the student knowledgeable about the existence of these areas and their importance to becoming a complete, fully competent Professional Engineer.

THE ATM SYSTEM

We now must provide a definition for an ATM system to see what can be done to provide educated personnel needed for pertinent ATM research, ATM technology development, and ATM engineering activities.

"An **ATM system** is a continuous operation, real time, multi-operator, multi-centered, semi-automated, large scale information handling system (ie., in military terms, it is a Command

and Control system) designed to handle in a safe and expeditious manner problems caused by the normal and especially the abnormal operations of air traffic in conditions of varying traffic density and traffic flow rates."

The ATM system deals with information inputs which can be classified as normal/abnormal/emergency, and which display different degrees of time varying uncertainty. It must be able to handle safely unexpected, emergency and abnormal operations at any time, and this requirement often limits the efficiency of its normal operational capability.

Given this definition, we can see five areas of technology and three other "operational" areas where persons trained for a career in ATM engineering need to be educated:

First, there are six areas of technology:

1. **Telecommunications**- particularly, radio communications (VHF,HF, UHF, and Satcom in all its forms), and all forms of datalink (Satcom, VHF, HF, and Mode S secondary radar). These should encompass various air/ground and ground/ground communications.

2. **Navigation** - particularly Satnav, GPS, ILS/MLS, Loran C, and the problems of differential navigation and hybridization of navigation systems.

3. **Surveillance** - particularly the capabilities of Mode S secondary radar, and the capabilities of ADS and ADS-B to supply more than just the traditional surveillance information in the form of past path and current position/groundspeed of aircraft. This extended surveillance information in the form of intended path and changes in the intended path is vital to higher performance, automated ATM systems.

4. **Aircraft Guidance/Control** - particularly the capabilities, limitations, and possible extensions of manual, and automated digital guidance and cockpit display systems such as the first generation FMS onboard current airline aircraft.

5. **Aircraft Performance** - particularly, knowledge about the performance limitations of various kinds of aircraft in climb, descent, takeoff, landing, and missed approach as a function of environmental conditions.

6. **Software Engineering** - since the new ATM systems will consist of distributed computers and local area networks tied to a similar complex at some distant location, and all of the operations will be controlled by software there is a need for good knowledge of modern software engineering.

Secondly, there are three areas of operational knowledge:

7. **Current ATM operations and procedures** for various types of ATM systems, and current operations of military, general aviation, and airline aircraft. The relationships of current procedures to the limitations of the currrent aircraft and current CNS elements of today's ATC system needs to be understood.

8. **Human Factors and Automation** which provides knowledge about the limitations of the human operators (both pilots and controllers) in using current and future display systems and different forms of automated decision support in the cockpit and at the ATC console. Inparticular, research is required in this area to produce new knowledge about mental workload and human performance in using various new forms of computer displays. Before good Human Factors research can proceed, there must be a good functional description of all ATM functions, processes and sub-processes, and the nested and complex interrelationships between these elements. This lack of a good functional description has inhibited the creation of a good plan for Human Factors research in ATM operations for the last 25 years.

9. **Operations Research** which can mathematically describe problems in handling stochastic traffic operations such as queuing or merging, which can characterize different types of traffic flows, or which can estimate flow capacities for various ATC processes such as landing flow capacity rates, takeoff capacity rates, capacity flow rate along an airway or across an airway fix, etc. It is also possible to estimate the encounter rates for different areas as a function of traffic flow patterns and traffic density. These mathematical techniques are needed to guide/direct and minimize the efforts currently being spent with another experimental technique of Operations Research called computer simulation.

These nine areas of knowldege exceed the normal content of graduate/undergraduate education for engineers

THE PROBLEM OF ATM EDUCATION

There is simply too much knowledge in the above nine areas to be included in the normal education of an engineer or doctor of engineering, and probably not enough demand to warrant a regular continuing curriculum to produce ATM engineers The answer lies in providing subsets of the nine areas as regular courses at universities for engineers concerned with the development of large scale computer systems in a wide spectrum of future applications other tham ATM systems Then, for engineers who become involved with ATM systems, their education could be supplemented with short courses as their work and career progression requires.

SUMMARY

1. The engineering of Automated ATM systems is a very multi-disciplinary activity, and there is no one person now capable of fulfilling the position of Team Leader or Project Engineer for an engineering team charged with developing a new Global Automated ATM system. This is a very critical deficiency when the 186 nations of ICAO must agree on a common design for the new global system. There must be enough detail in the common design to show a capability for simultaneous operations with the current system, and the acheivement of phased benefits during a phased implementation of the new system over a very long period as the needs of the high traffic density areas arise around the world. This means the new GATS procedures must be established and agreed before the design can be accepted. No one knows how to do this at this point in time.

2. The role of Human Factors cannot be minimized. It is paramount since the system will eventually be operated by human controllers and pilots in the airspace over all the nations of the world. The system must be designed for them, and retraining in the new system and their need to probably work both th old and new systems is a major factor in the design of the new system. There is a need for good research in many Human Factors problems which prevents the engineering from going forward at this time. This deficiency has been recognized for over 25 years, but the research has not been funded since a good research plan has not been created.

3. The task of introducing automation into ATM will be a long an tedious effort over the next 25 years. It will require a greatly expanded effort over what has been expended over the last 25 years. The need to create some formal educational activities is long overdue. It can still contribute to creating an efficient path to future progress.

Airspace Organisation and Optimisation

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1. Historic background

The beginning

At the beginning it was easy. Until the early 70th-es only some 5 miles wide air-corridors were available for the international traffic, anything outside was strictly prohibited area. Even these corridors were frequently confined to determined levels, usually from FL 160 to FL 310. Military traffic enjoyed absolute priority, restrictions were implemented even for a simple fighter's flight. Under the law, the Minister of defence was the supreme co-ordinator of the airspace. Route-planning precluded the possibility of overflying danger or restricted areas, it was no matter weather they were active or not.

Those few airlines, which planned flights via Hungary despite these, met another difficulty, namely the requirement of preliminary permission. They had to have the clearance of the Aviation Authority at least 5 days before the flight, a petty administrative mistake lead to sure rejection, any minor change (e.g. type) required another permission. It is understandable, among these conditions, the civil traffic demand was restricted to 120 - 160 flights/day.

1972 ICAO

Some changes ensued in 1972, when Hungary - first from the region - joint the ICAO. Corridors widened out to 10 miles, we adopted the FL system, the rigidity eased a little, we tried to consider the ICAO standards. Until the middle 80th-es the strict military control turned a little bit flexible civil demands were considered at tactical level. The traffic grew up to 300-350 movement/day.

Early 90th-es, essential changes

The first basic changes came up at the end of the 80th-es, together with the political changes. The corridors were replaced by routes, when the military traffic paused, diverging was possible. Civil interests were considered during strategic planning.

The second decisive changes came up in 1991, after the eruption of the South-Slavonic crisis. The traffic increased abruptly, up to 1000 IFR movement/day. New routes were implemented according to traffic demand, military traffic had to be executed within assigned TRAs. Civil interests were considered at every level of airspace management. Fortunately, by the withdrawal of Soviet troops, the military demand dropped down significantly. In 1992 Hungary - also first in the region - joint Eurocontrol, and the re-organisation of the whole airspace structure and management went on very fast, in accordance with the Eurocontrol standards. Hungary joint the FUA concept among the first states. In 1994 TSAs were assigned for military traffic. AMC was set up in 1995, civil priority was acknowledged in law.

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

Naturally, a huge technical-operational development was necessary, and the re-organisation of the whole air defence system was unavoidable. During the rush hours one aircraft/20 second enters to our airspace, the confident identification must be solved.

2. Hungarian peculiarities

In the course of strategic planning the following peculiarities must be considered:

- 85% of IFR traffic flows in the upper airspace, above FL 245
- There is significant difference between winter and summer traffic
- The highest demand is between 10-16 UTC
- Increased demand during weekends

The yearly increase is situated in the next graph:

3. Airspace classification

At present 3 main airspace categories are ruling in Hungary:

- Cat. „A" above FL 195 and within Budapest TMA
- Cat. „C" between 7500' - FL 195
- Cat. „G" from ground up to 7500'

Beside these we can find cat. „D" airspace as well, where the ATS is provided by Kosice TRCC/TWR. There are TSAs assigned for OAT traffic. Some minor VFR aerodromes have own TIZs, for more airspace they appeal for AMC.

4. ATS delegations

Only a few weeks ago, from 04.April 1997 mutual ATS delegations took into effect between Austria-Hungary and Slovak Republic-Hungary. Simplified sector lines were staked out between ACC Wien and Budapest above 7500', so the boundaries of ATS don't follow the geographical borders. We mutually consider or classifications in our procedures. We have already started negotiations for some kind of „unified" classification along the boundary.

A portion of route between BUD-FMD crossing Slovakian airspace. The ATS is delegated to ACC Budapest above FL 155, while within the already mentioned „D" class airspace the ATS is delegated to the Slovakian Kosice TRCC/TWR. There are negotiations in progress to create a simplified ATS boundary, similar to the existing Austrian-Hungarian one. According to the first signs, the ATS delegations fulfilled our hopes extensively, the possibilities of strategic planning widened, the management of traffic became much more flexible and simple, the capacity increased.

A typical example for the growing possibilities of strategic planning the implementation of the BUB-FMD route. Since long, it was one of the most serious problems of Budapest ACC, that the westbound traffic out of Budapest, and the eastbound traffic inbound to Wien airport used the same route (TPS-GYR). These traffic streams crossed their levels, which required frequent radar vectoring. It is typical, while Budapest ACC has five sectors, half of the radar-vectoring procedures were used in the west sector. Even these procedures were confined by the closeness of the state boundary north, and the Budapest arrival traffic south. These appreciably limited the capacity of the west sector. By delegation of ATS, these two main traffic stream was separated strategically, the number of radar-vectoring decreased to minimum, consequently the sector capacity increased by 15%.

5. Dynamic management

Hungary joined the EATCHIP Flexible Use of Airspace (FUA) concept among the first states. The management of the whole airspace is in accordance with this. As in the majority of the states, the management is divided for three main parts:

1. Strategic planning
2. Pre-tactical planning
3. Tactical phase

Strategic planning

The strategic planning is done mutually by Civil and Military Aviation Authorities. During the planning process they gauge and co-ordinate civil and military demands, and work out the necessary procedures. In case of needs, they implement new routes, modify TSAs. According to the FUA concept, for sake of optimised utilisation of the airspace conditional routes (CDR) were implemented. With the introduction of FUA concept, the possibilities of strategic planning widened further. A typical example for this is the implementation of route UB43 in April 1996.

Before April 1996 Budapest ACC had two main neuralgic, capacity-reducing points. BUG in the East sector, at the crossing of the main streams, and BABIT, where the crisis-area avoiding traffic flows. The high southbound traffic demand over BUG excluded the dualisation of BABIT for two tracks, and confined the capacity of east sector as well. UB43 was available on weekends only, considering the fact, that it crossed the „razgon" route of Kecskemét air-base, the route, where the flights over supersonic speed is executed. With FUA procedures, we could implement UB43 as CDR1. Naturally we had to work out the bypass procedures, which suppose close civil-military co-operation.

Considering the fact, that a CDR1 can be planned in RPLs, the majority of the Scandinavian-Greece traffic stream could be redirected to this route, via the rarely utilised north sector, where free capacity was available. Consequently, the load of BUG was reduced, which made possible the dualisation of BABIT (BABIT-TOMPA), so the traffic stream avoiding the crisis area could use two tracks instead of one. The final result:

1. The capacity of East sector increased from 32 to 38 (19%)
2. The capacity of South sector increased from 35 to 43 (23%)
3. By the better utilisation of North sector, the global capacity of Budapest ACC increased by 20%
4. Despite of 6% traffic increase, delays caused by Budapest reduced significantly

Pre-tactical planning

The pre-tactical planing is the task of the Airspace Management Cell (AMC), which was set up in March 1996. The AMC is manned by the authorised participants of civil and military ATS, and works with close co-operation with the FMP, which provides AMC with the necessary data for planning. The AMC must consider the priority order during decision taking, which is set up by the Authorities, consensus desirable. Very important rule, that in the lack of consensus the final decision is made by the civil supervisor, carefully weighting all circumstances. The priority order is authoritative, but the AMC must solve its task - weighting possible alternates, modifying some periods - to fulfil all requests. After decision the AMC prepares the Airspace Use Plan (AUP), closes CDRs1, opens CDRs2 accordingly.

Some practical examples for AMC operations:

- Papa air-base is planing flights over supersonic speed between 10-13 and 15-17. These flights have primary effect on the South sector, mainly on the TOMPA-SVR westbound traffic. These traffic must be redirected to the assigned bypass route (TOMPA-TIRAT). It is obvious that it can be solved in the easiest way, when the demand in the South sector is relatively low, or it is high, but inside this, the proportion of the redirected traffic is low. The FMP provides AMC the necessary data (expected traffic of South sector and TOMPA westbound). The figures indicate, that the first period should be executed between 09-12, while the second one can be done as planned. The AMC takes decision accordingly, prepares AUP, closes temporarily CDRs.

Kecskemét air-base is planning supersonic flights from 14 to 17. This time AMC analyses the situation on UB43, which reflects high demand between 15-16. Considering this, AMC offers two periods for the military planers to choose, between 12-15 or 16-19. According their decision, the AMC arranges the closure of the CDR1, and publishes the bypass routes. In this very case, the Hungarian AMC co-ordinates with the Slovakian AMC as well.

Tactical management

The AMC is continuously monitoring the situation of the airspace, and in some cases it is executing tactical tasks. Considering the actual changes it prepares the Updated Airspace Use Plan (UUP). In the cases of unexpected demand it co-ordinates between the parties involved.

6. Ongoing projects

In the near future the main projects are being developed:

1. The MATIAS project
2. Re-classification of airspace
3. Further development of AMC

MATIAS

The MATIAS project is introduced in a different presentation. However, it is important to mention here, that in the field of civil-military co-operation - with the necessary technical means - the tactical co-operation will be more determining, the education of the OAT controllers has recently finished. Fortunately all these coincide with the planned introduction of FUA Level 3 in 1998. The development of the AMC considers this fact.

Airspace re-classification

Considering the Hungarian peculiarities the introduction of new airspace categories, and advanced VFR control are being planned. The main elements of the concept under project are the followings:

- Airspace cat. „G" from ground to 5000' (no radio contact required)
- „E" between 5000'-FL 125 controlled by the FIC, which is planned to be developed to Advisory Service
- „D" where it is reasonable, e.g. along the Hungarian-Austrian border west of GYR
- „C" between FL 125-195, and within the TMAs/TSAs
- „A" above FL 195, and in the TMAs where justified

It is very important to recognise those Hungarian features, that, meanwhile the military demand is confined for mid-days, the VFR one is much higher during weekends. Accepting this, two classifications can be introduced within the lower airspace. It means, during weekends the classification of TSAs can be changed from „C" to „E" or „G". Furthermore, in accordance with FUA concept all kind of airspace - excluding prohibited areas - will be managed by AMC, including danger areas.

AMC development

In accordance with FUA concept and the Hungarian peculiarities the developed AMC will provide the next tasks:

International tasks:

- Preparation and publication of AUP and UUP
- Checking and evaluation of the CRAM
- International co-ordination mainly with the cross-border CDRs
- Co-ordination with NATO and USAF

Supervision of state flights

Internal tasks:

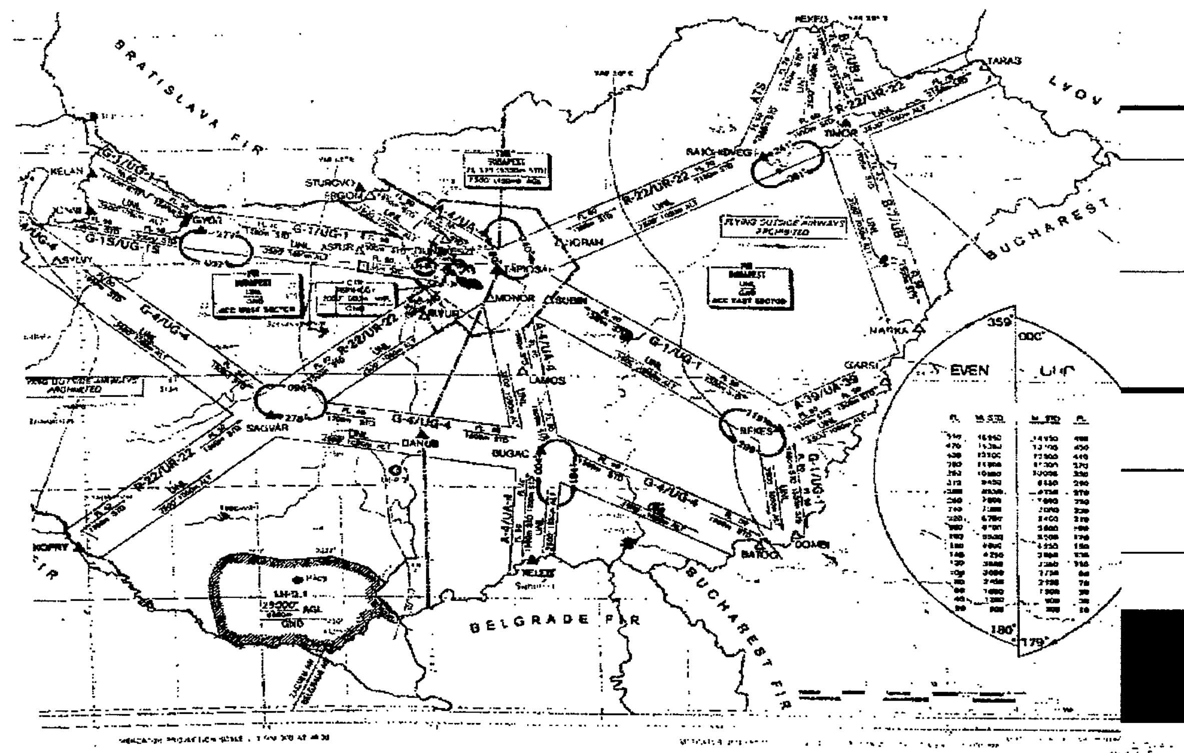
- Continuous information provision for VFR flights within „G" airspace. The form of presentation will be the next:
  - By fax/phone
  - Continuous, frequently refreshed information on the Teletext near the Airport Information
  - Automatically by fax for VFR aerodromes on request
  - Using Internet, primarily for foreign users planning VFR via/to Hungary. This information can contain further information, e.g. the VFR rules in Hungary.
  - Continuous co-operation and refreshment with the users of restricted and danger areas

7. Summary

As you could see, the organisation of the Hungarian airspace is in accordance with the international requirements, continuously integrates the recommendations of the Eurocontrol and the NATO, the management and permanent development of the airspace are daily tasks, and the result of the good job of our military and civil experts.

Gábor Mavrák

AT THE BEGINING IT WAS EASY...



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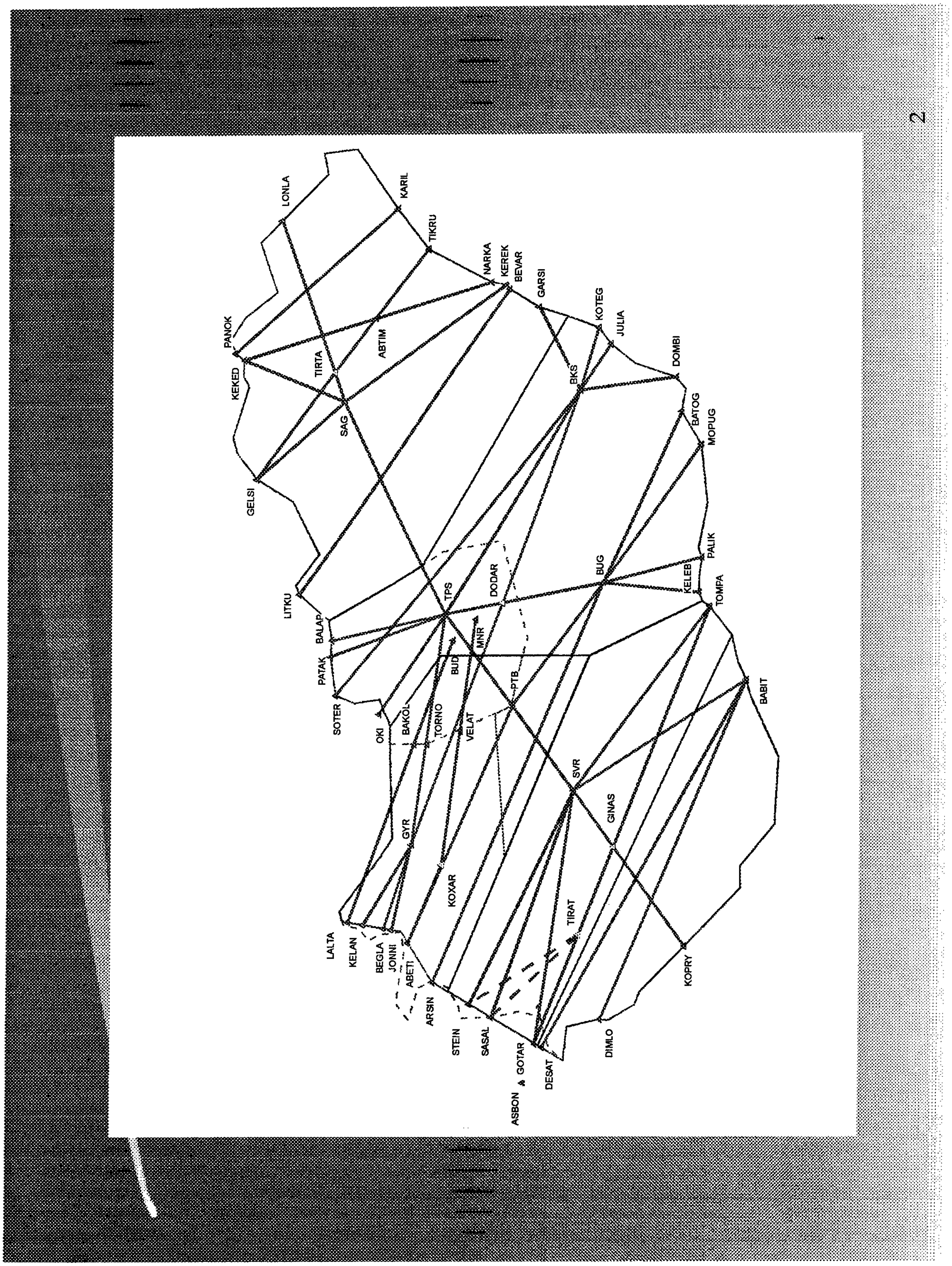
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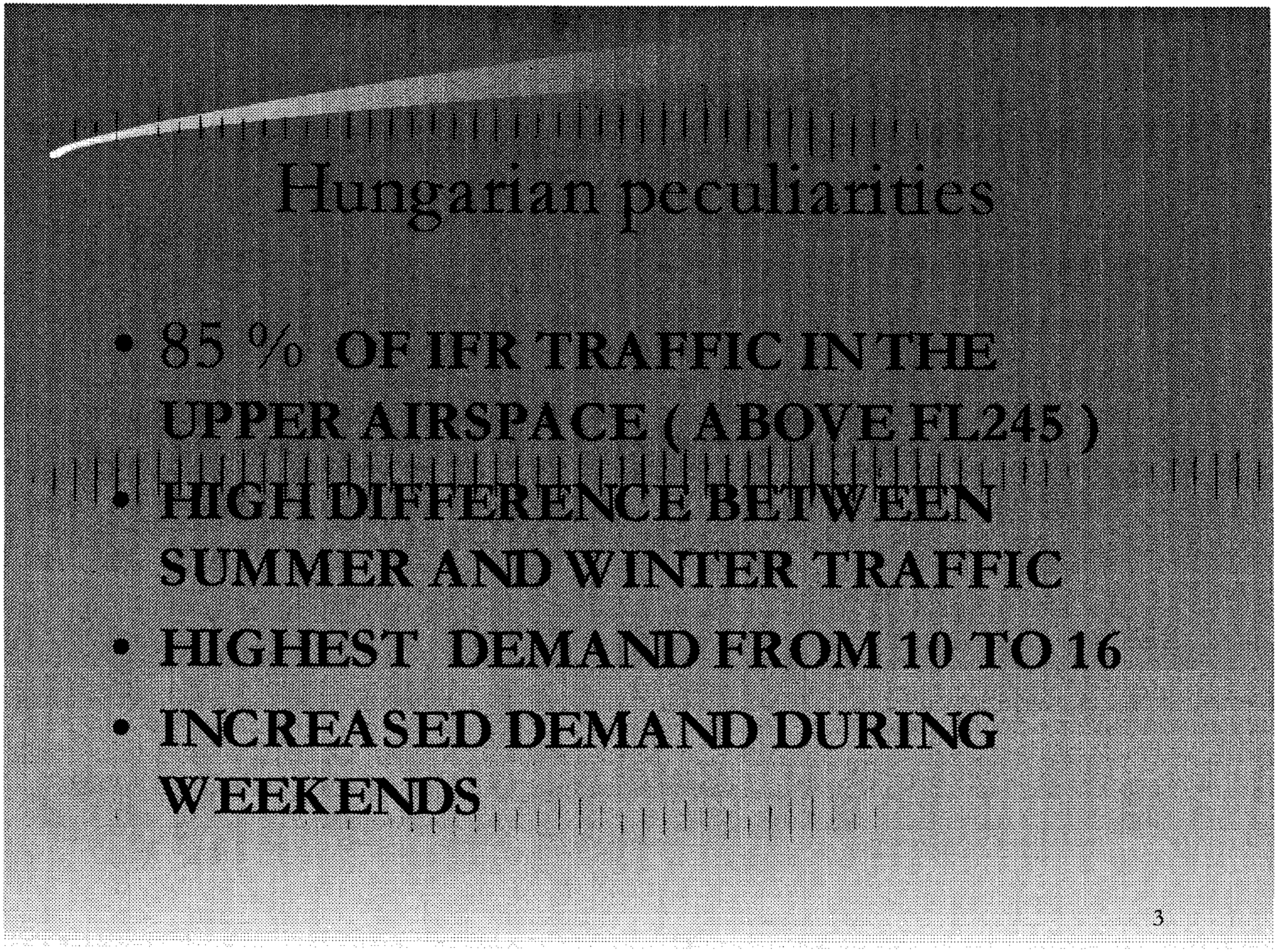
Hungarian peculiarities
• 85 % OF IFR TRAFFIC IN THE UPPER AIRSPACE (ABOVE FL245)
• HIGH DIFFERENCE BETWEEN SUMMER AND WINTER TRAFFIC
• HIGHEST DEMAND FROM 10 TO 16
• INCREASED DEMAND DURING WEEKENDS
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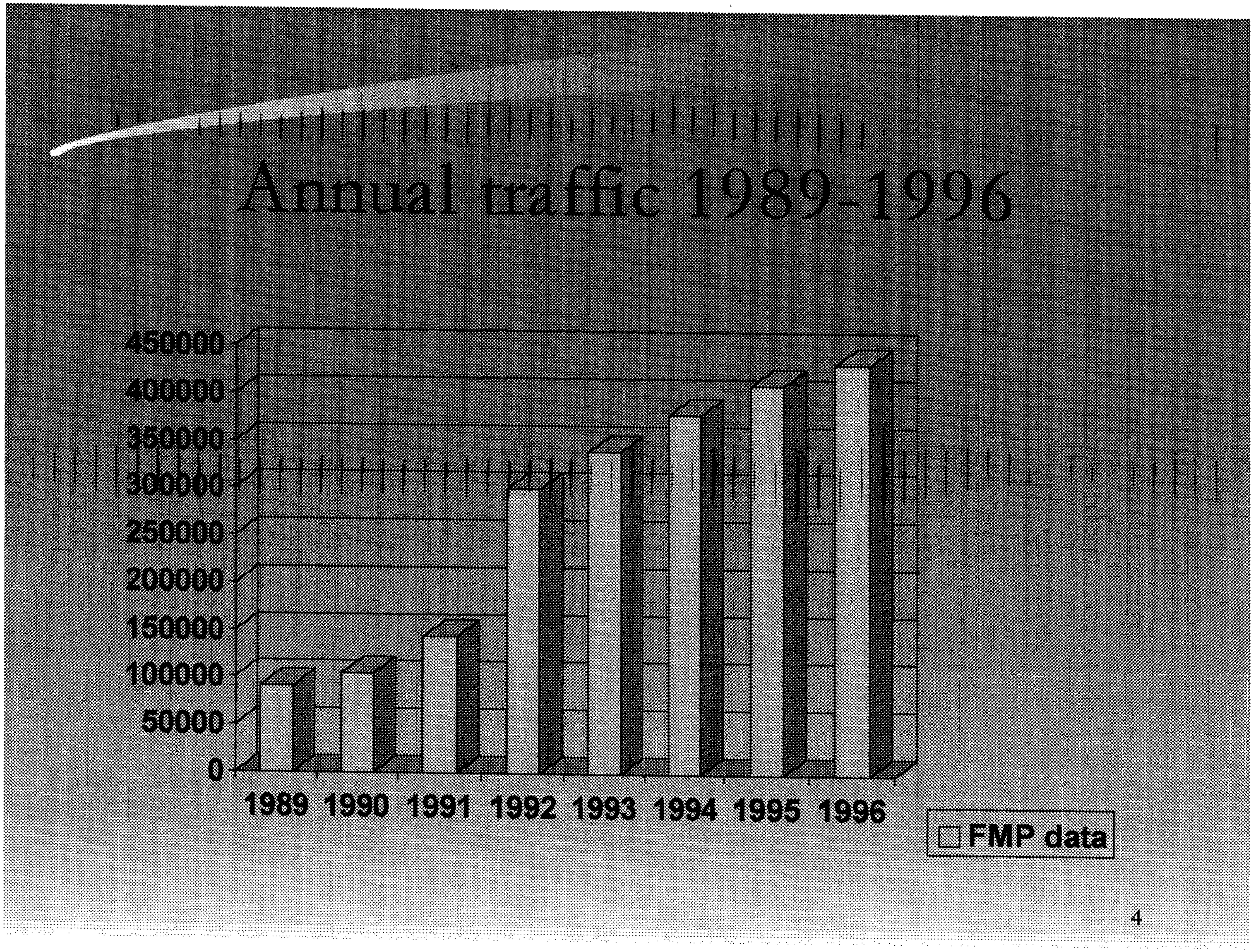
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FMP data
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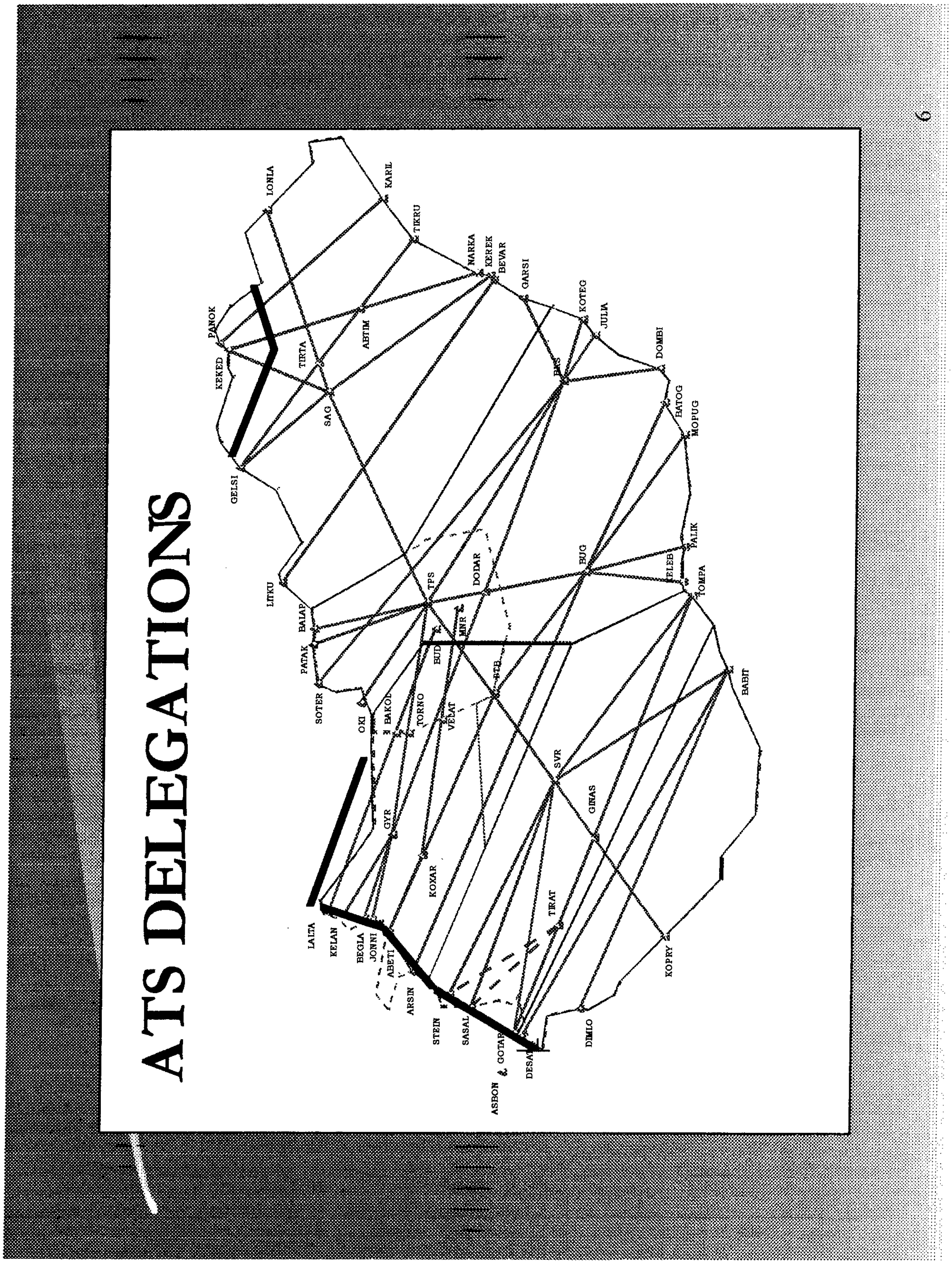
CLASSIFICATION and STRUCTURE

- A Fl 195 FL 460
- C 7500' FL 195
- G ground 7500'

- TMA
- TSA
- TIZ


ATS DELEGATIONS
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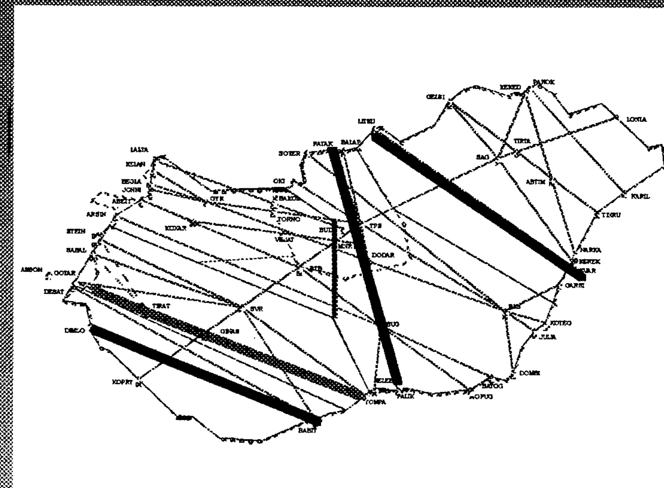
CDRs, STRATEGIC PLANNING

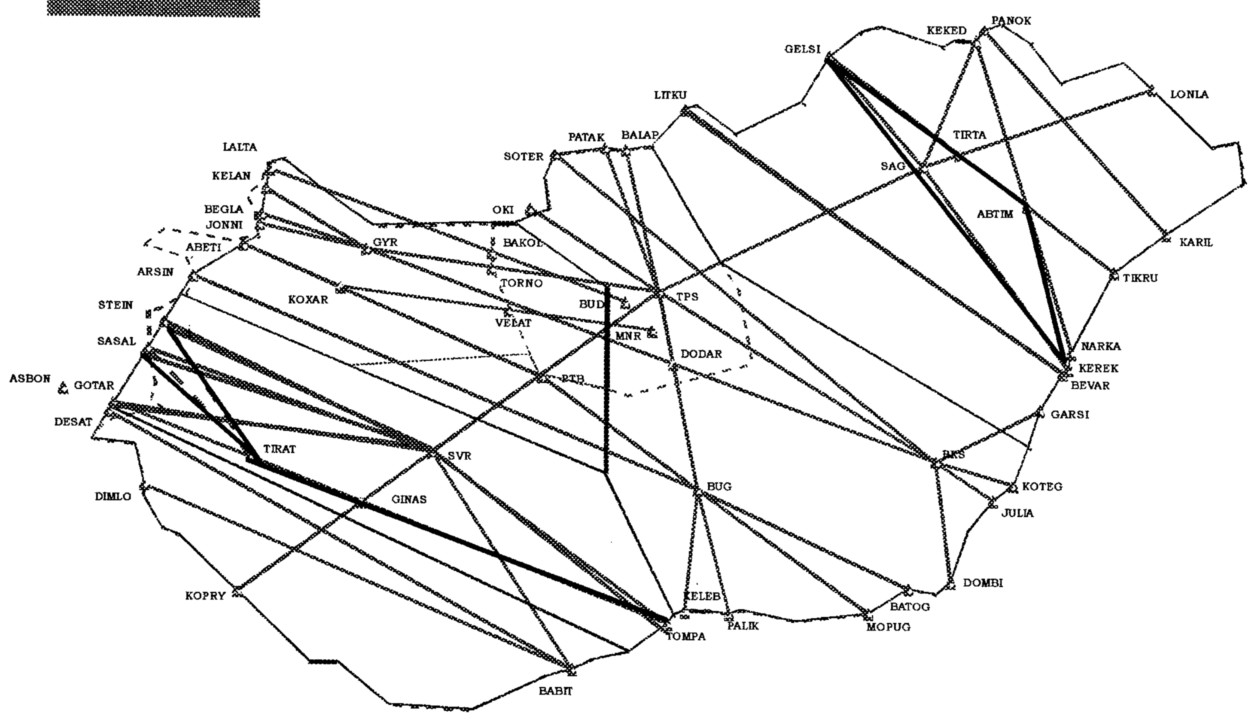
- EAST 32 > 38
- SOUTH 35 > 43
- ACC + 20%
- 6% INCREASE
- LESS DELAYS



AMC

• COLLECTION	• FMP DATA
• ALLOCATION	• PRIORITY ORDER
• AUP - UUP	• ACA > CFMU
• OPENING CDRs 2	• 3
• CLOSING CDRs 1	• 5
• PUBLICATION	• CRAM /CFMU /
• MONITORING	• FAST REACTION

CDRs



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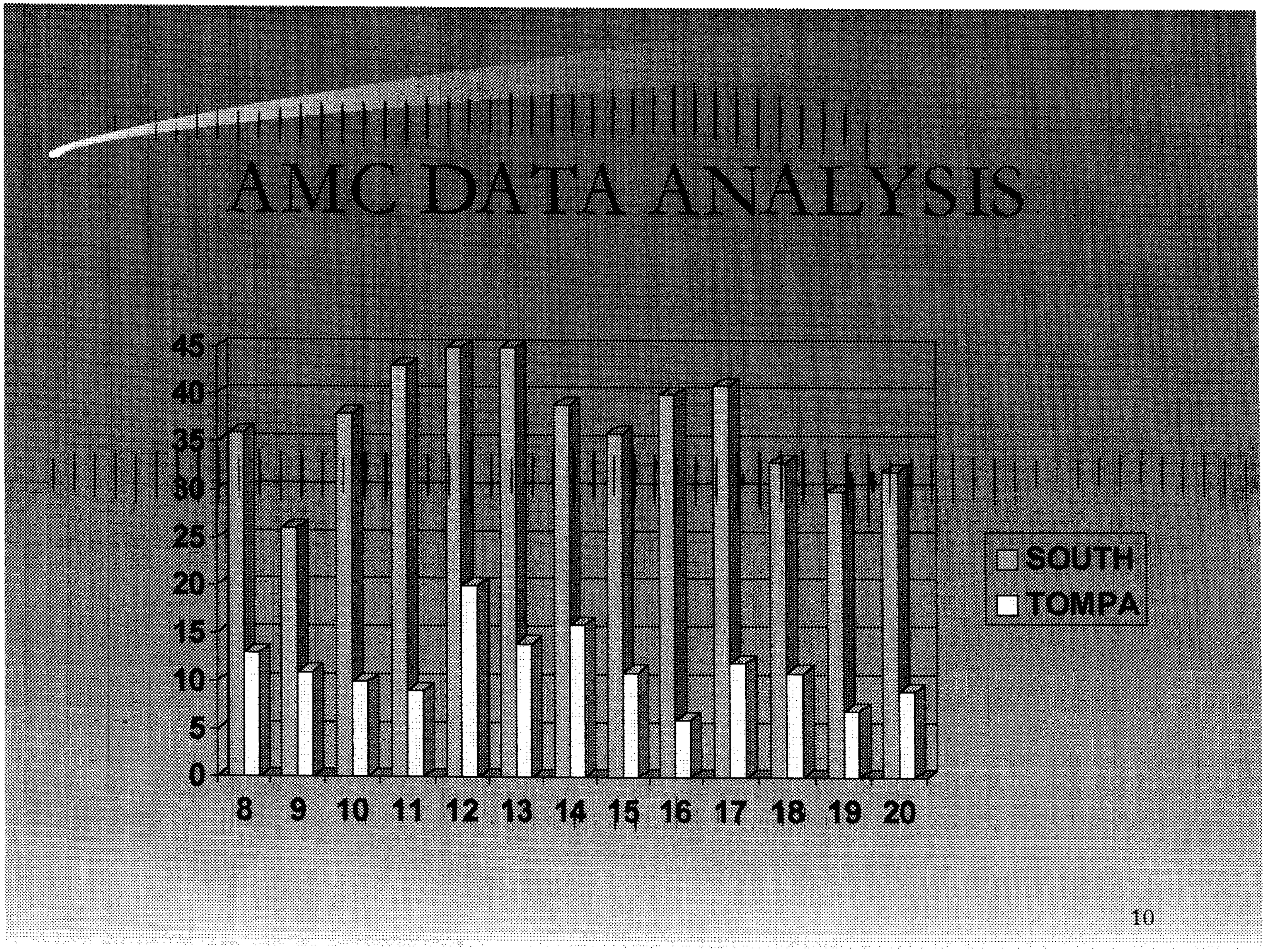
AMC DATA ANALYSIS
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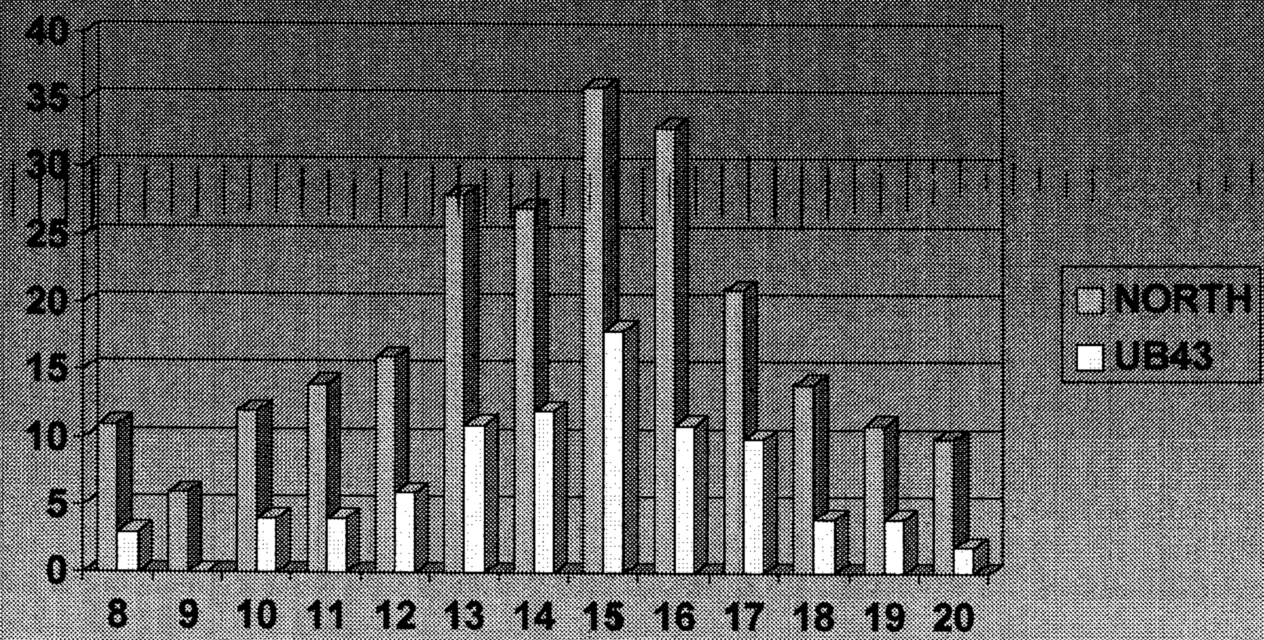
AMC DATA ANALYSIS



AMC DEVELOPMENT

- INTERNATIONAL
- AUP, UUP
- CRAM ANALYSIS
- COORDINATION
- NATO, USAF
- STATE FLIGHTS

- DOMESTIC
- INFO PHONE/FAX
- TELEFAX INFO
- VFR AIRPORTS
- INTERNET
- DANGER AREAS
- UPDATING

Human role in ATM : Support for Decision Making

by

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Abstract

The ever increasing demand for air traffic is silting up the Air Traffic control system. As a response, the high level management moves towards a business approach: increase system capacity to meet the demand, monitor the quality of the product, in particular safety, and reduce the cost.

Air Traffic Control is a complex task that involves human controllers and machines. Today, there is a consensus such that, at least in the enroute environment, the human controller is a major bottle-neck. Accordingly, the introduction of a higher level of automation is considered to be the way forward.

The EATCHIP programme of Eurocontrol, in close cooperation with its member states is defining the EATCHIP Phase III ATC system generation that aims to improve ATC capacity and flight economy whilst at least maintaining the present safety level. It intends to achieve this by introducing automation in a human-centred approach.

The paper describes some human characteristics related to the introduction of automation in general, current trends in future system automation and associated safety risks. The paper concludes with a proposal for a pragmatic way ahead including how to gain controller acceptance.

1. Introduction

The ever increasing demand for air traffic is silting up the Air Traffic Control system. As a response, the high level management moves towards a business approach: *increase system capacity* to meet the demand, *monitor the quality* of the product, in particular safety, and *reduce the cost.*

Air Traffic Control is a complex task that involves human controllers and machines. Today, there is a consensus in that, at least in the enroute environment, the human controller is a major bottle-neck. Accordingly, the introduction of a higher level of automation is considered to be the way forward.

In order to keep the developments on the right track, it is essential to evaluate the proposed concepts using objective criteria. These include the impact on *safety*, ATC *capacity*, flight *economy,* technical *feasibility,* and, by no means the least, *cost-benefit* aspects. Likewise, the human role in the future ATC system needs to be considered.

It is expected that the controller will remain an active part of the control loop for a significant period of time. Developments that follow the directions of the "human centred automation" concept are underway. They provide the controller with automated tools to make his/her decision making more efficient.

This paper describes some human characteristics related to the introduction of automation in general, current trends in future system automation and associated safety risks. The paper concludes with a proposal for a pragmatic way ahead including how to gain controller acceptance.

2. The ATC "*dream*" system

The ATC "*dream*" system provides a global optimisation for all air traffic from push back at departure airports until the shut down of the engines at

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arrival airports, considering the interest of all parties involved. Passengers expect a safe arrival and adherence to the published schedules, operators want to fly at minimum cost and the public authorities wish to minimise the impact on the environment. It is clear that such a global optimisation is a very complex issue with many conflicting requirements which can not be handled without the help of automation. The compromises sought will have to consider, besides political considerations and technological capabilities, the cost-benefit aspect of the possible solutions. As this last aspect has a direct impact on the demand for air travel and its efficiency as a whole, we all know that today we are still far away from this dream and that there is a long way to go.

3. The present situation

During an IFR flight from A to B, the safe and expeditious progress of the flight is constantly ensured by ATC. To that effect, the total airspace is divided into ATC sectors which constitute contiguous volumes of airspace with vertical as well as horizontal boundaries. Area Control Centres (ACC) and terminal control facilities thus comprise upper and lower airspace sectors, as well as Terminal Manoeuvring Areas (TMA). The latter constitutes the lower airspace around an airport. In each sector an *executive controller* is in direct contact with the flightcrew of all aircraft for which he or she is responsible. Depending on the traffic load in the sector, the longer term planning of the traffic flow through the controller's *own* sector and the coordination with the *adjacent* sectors is done by the *planning controller* possibly helped by further assistants.

The airspace structure has continuously evolved. As the number of aircraft a control team can handle is limited, the increase in air traffic resulted in a reduction of the volume of airspace for certain highly loaded sectors. This lead to an equivalent increase in the number of sectors that the aircraft have to fly through. This geographically limited responsibility results in a situation where optimisation can only be performed at sector level with relatively low co-ordination with adjacent ones, placing us far away from the "dream system".

Today the point has been reached where a further reduction of the volume of airspace per sector does not increase the overall capacity. This is due to the increased workload associated with the co-ordination with neighbouring sectors. In order to avoid the overloading of sectors, flow control restrictions came into force which resulted in the allocation of "*slot times*" for flights through such areas during busy periods. *The capacity barrier has been reached!*

A further increase in capacity can only be obtained through an increase in the efficiency of the control team such that, at an equivalent workload, more aircraft can be controlled at the same high level of safety. Where can we improve?

3.1 The decision making loop

Figure 1 presents a graphical description of the ATC decision making loop. The flightcrew provides Flight Director (FD), Auto-Pilot (AP) and Auto-Throttle (AT) inputs assisted by the Flight Management and Control System (FMCS). The aircraft positions are tracked by radar systems. In the Flight Data Processing System, the 3D positions of aircraft are linked to available flight plan information. This compiled "*present traffic situation*" is presented on the Controller Working Position. On the basis of this information, the controller builds in his mind a representative picture of the observed traffic. This is often referred to as "*situational awareness*". He/she then estimates the probable evolution of the traffic, identifies potential problems, elaborates tentative solutions, evaluates their likely consequences and decides on the implementation. The executive controller communicates the instructions to the flightcrew.

The "*present traffic situation*" is periodically updated, reconsidered and the loop is repeated.

3.2 Introducing automation in the ATC loop

In most ATC systems in operation today, automation is limited to radar data and flight data processing. These systems merge the information from different sources and perform monitoring and consistency checking. In more advanced systems, a Short Term Conflict Alert module will warn the controllers for a potential loss of minimum separation between aircraft. Although the individual algorithms used may be very complex (e.g. multi radar tracking, etc.), in general, these machines perform straightforward data processing and present the results to the controllers through a convenient Human Machine Interface (HMI).

Indeed the level of the automation in present systems is limited to the conversion of "*raw*" data to valuable "*information*" that can be more efficiently used by the human. But, very limited functionality has yet been implemented to help the controller in his *decision making process*.

In a manufacturing or industrial control process, automated tools can be introduced with a high chance of success as clear boundaries can be established between the responsibilities of the humans and the machines involved. However, the introduction of automated tools that provide *decision support* to humans in a real-time system, i.e. a system that typically operates under time pressure, is a considerably more complex task. By *time pressure*, we mean that the time can not be "*frozen*" to compensate for insufficient human reaction speed. In particular,

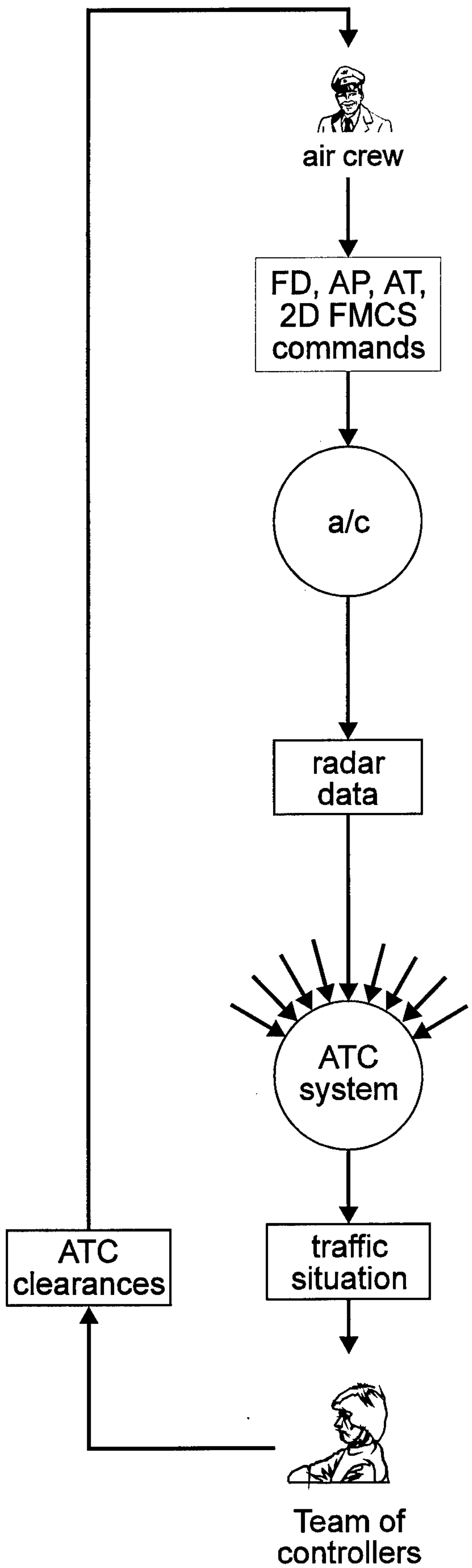

Figure 1 ATC loop

this aspect affects the safety level of the system as, when the capacity barrier is approached dangerous situations can easily develop. In contrast this "time freezing" option allows automated manufacturing processes to run close to capacity limits at acceptable risk levels.

3.3 Role of the Man in the ATC loop

To perform their role in the present Air Traffic Control environment, controllers rely mostly on indirect information which is:

provided before the flight,
sensed by ground-based installations,
transponded from aircraft,
computed from collated data,
radioed by flightcrew,
telephoned by other controllers.

Once captured, processed, stored and sustained, this information is presented to the controller through a Human Machine Interface (HMI). Figure 2 depicts the Decision-Making process of the controller which is based essentially on the prediction of the medium-term future. If the predicted future seems unsatisfactory then remedial action is undertaken in order that safety is assured. This Decision-Making process is a distributed one because several controllers are often involved and good system support for co-ordination is therefore required.

The performance of the overall control loop is limited by the performance of the weakest component in the chain. In terms of capacity for the enroute environment, it has been identified that this is the Air Traffic Controller. To optimise the overall performance it is essential to understand the specific merits and limitations of humans in the particular tasks.

4. Human characteristics

In any task to which the human is assigned, information must be perceived, interpreted and either responded to immediately or stored in memory for later action. Finally, the consequences of a response become available again to perception as feedback. Generally feedback (especially when it is immediate) creates a positive impact on the performance, in particular for the novice.

The performance of the activities illustrated in Figure 2 can be described in terms of capacity of two generic forms: (1) the limits in the speed of its functioning and (2) the amount of information that can be processed in a given unit of time. There are also limits to the total resources available for information processing, i.e. the mental energy (Reference 1).

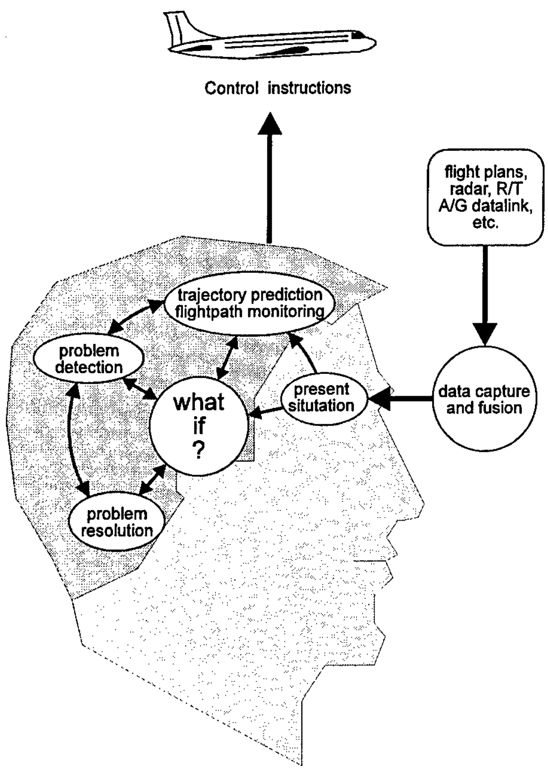

Figure 2 Human Decision Making Process

The characteristics that describe the human performance are summarised below. Many reference books have been published on these subjects. We found that Reference 2 holds an excellent compilation of papers indicating the state-of-the-art in Human Engineering.

4.1 Perception of information

The decision making process of the controller is based on the mental picture of the actual traffic situation. In order to achieve this, a controller needs to gather large amounts of perceptual information, then store this in his working memory, before responses are initiated.

The perceptual recognition can be described as the association between an incoming event and a recognised "template" that is stored in the memory (References 3-4). For example, the perception of the letter "A" results both because the features of the "A" are analysed by the visual system and because "A" is a familiar concept and therefore has a strong representation in the memory. The speed of the recognition process and the accuracy with which it is performed are important parameters for the optimisation of human - machine interfaces.

The quality of perception is affected by the expectancy supported by the context of the event and the sensory quality of the event. The relation is illustrated in Figure 3 from Reference 2. In this experiment, test persons were presented with sentences of the form, *"I'll complete my studies at the .... "*. The final word would be displayed for very brief duration thereby producing a degraded sensory stimulus. The experimenters controlled the duration of the stimulus and could vary the amount of words in the context between nothing, four and eight.

The results illustrate the trade-off in recognition accuracy between stimulus quality and redundancy. In effect when the amount of information that needs to be transmitted to the controller in a given time frame increases, it becomes more essential that the quality of the presentation is optimised in order to maintain an acceptable perception rate. The results also indicate that the order of magnitude of textual information that can be transferred visually is very limited, namely only *a few bytes/sec.*

4.2 Working memory

The human memory consists of two main components: the long-term and the short-term, or working memory. The long-term memory holds our permanent store of information and facts about the world and relates to issues of learning and training. The working memory is the limited store of "conscious" information.

Complex decision making often relies on the working memory of the human to *entertain*, *weigh* and *compare* the various alternatives. No surprise that decision making suffers from a number of memory related drawbacks.

The capacity of the working memory is limited by the number of unrelated items that it can hold. Even when full attention is devoted to rehearsal, this number is ranging somewhere between 5 and 9, also known as the 7±2 limit (Reference 5). This limit is dangerously restrictive in complex systems. It often leads humans to process perceived data incorrectly. For example, the problem becomes apparent in menus that offer sets of options. Ideally, within any given list, these options should be constrained to no more than the capacity of the working memory.

The association that exists between perception and the working memory is relatively strong. It can be reinforced by the finding that a single object, e.g. the callsign of a flight, can act as a sort of "chunk" that supports the memory of its attributes. Humans have a considerably better memory for a small number of objects with many attributes, than for many objects with a small number of attributes (Reference 6). Translated to ATC, the type, altitude, airspeed and heading of two aircraft would be better retained than the altitude and airspeed of four aircraft although in each case eight items are to be kept in working memory.

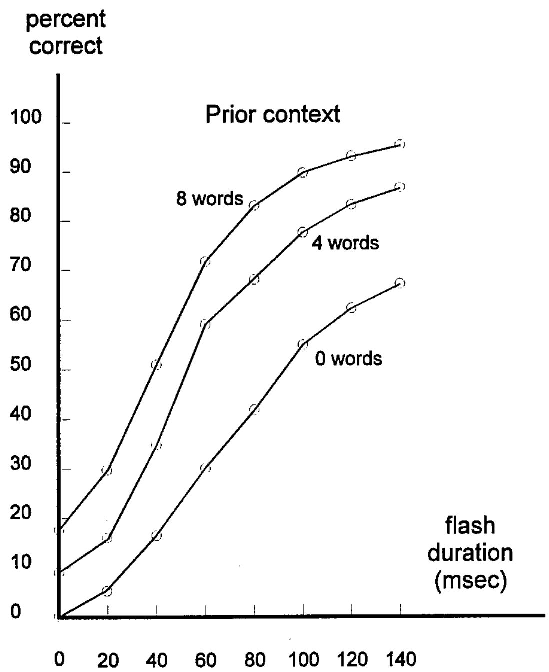

Figure 3 Stimulus quality and redundancy

4.3 Making the choice

An ATC problem can often be solved in several ways. Each of these potential solutions has associated attributes like workload, safety, cost, effectiveness, etc. In the decision making process, first, a quality factor is established for each potential solution. It is derived by multiplying "*importance weights*" on each attribute by the attribute "*value*". The solution with the highest value is the optimal choice.

As controllers must perform the mental multiplication necessary to integrate all attributes of all solutions, the major limitations in human choice performance result from the load on the working memory. Instead of loading the memory in this fashion, people often resort to simplifying strategies in which major components of the information are ignored. For example, they may attend only to the most important attribute and subsequently eliminate from consideration all solutions that do not score highly on that attribute (Reference 7). To a certain extent, "importance weights" and attribute "values" are subjective. This explains why different controllers favour different solutions to the same problem.

4.4 Use of predictive displays

Humans are not very good at predicting future states on the basis of the "now" information. In addition, this creates a heavy load on the limited cognitive resources of the controllers. It is not surprising that predictive displays have almost been uniformly found to improve control and scheduling performance (Reference 8).

Predictive displays can work according to different principles. One possibility is *input preview*. The system knows or estimates the inputs to which the controller must respond before they arrive. This allows the presentation of a *default response* that is computed by the system on the basis of the available information, e.g. the automatic positioning of the display cursor on the most probable response in a menu.

When it is not possible to establish the future state of the system with sufficient certitude, the future state may be inferred by a *fast computer simulation*, e.g. the predicted flight leg, Conflict and Risk Display, etc. The information is generated on the basis of the current system state, available planning data and expected inputs.

If the future trend is not sufficiently known, it can be envisaged that the *approximate* future system state is obtained *through linear regression* using the present aircraft state and history data. A typical application is the Short Term Conflict Alert function available in some Flight Data Processing Systems.

Controllers will use predictive information as long as it is accurate. However, the accuracy of the information degrades with look-ahead time. Its quality will reduce more rapidly as the environment has a greater uncertainty (wind, aircraft performance, etc.) and when the humans in the control loop i.e. the pilots and controllers, have a greater opportunity to exercise control. These factors affect how far into the future the predictive information should be presented to the controllers ("look-ahead" time).

Note that, to a certain extent, the use of information presented to the controller through predictive displays also complicates the decision making. This is due to the fact that a certain element of uncertainty or risk needs to be added, i.e. *what you see is probably NOT what you are going to get.* When considered in conjunction with the attribute "values", this could sometimes lead to further deviation from optimal behaviour. This is because the human intuitive estimates of *probability* and *value* do not always correspond to the actual objective values of these quantities. In particular, for predictive displays these are very difficult to assess or interpret.

4.5 Impact on HMI design

Following the concepts of "human centred automation", to a large extent, the HMI is the driving force for the definition of the required functionality of the new automated tools. With the increase of the traffic density in a sector, the *information content* of the data displayed on the Controller Working Positions needs to be enhanced. For the next generation of operational ATC systems this is achieved through more intelligent HMIs (Reference 9). Information filters that

control the *presentation* of the data pertaining to a given flight in function of the information contents are introduced. Redundancy is added through Sector Inbound Lists, Message Windows and the dynamic formatting of the radar identification label on the Controller Working Position. However, by adding redundancy, the total amount of information to be transferred to the controller team increases thereby degrading again the sensory stimulus. Optimisation is not obvious and requires a lot of experimentation.

Another potential step forward could be the move towards "*stripless systems*". This approach concentrates the presentation of all relevant flight information onto one medium thereby increasing the maximum data throughput. However, in order to maintain a given safety level it will be required to provide some backup facilities in case of contingencies.

5. Trends in automation development

The *EATCHIP Phase III operational concept* (Reference 10) aims to optimize the Air Traffic Control in the individual sectors. It is intended to achieve this by introducing "stripless" Controller Working Positions supported by automated tools such as Medium Term Conflict Detection, filtering problem/non-problem traffic (Co-operative Tools) and safety nets like Short Term Conflict Alert. In the EATCHIP Phase III concept all aircraft are always under positive control by successive ATC sectors.

Free Flight (Reference 11) holds that aircraft are totally free to decide where and how to fly without requiring a specific clearance from ATC. Air Traffic Control only intervenes if a risk of conflict occurs, and, in areas close to the airports of departure and arrival. Prerequisites are the capability to obtain position information through the use of GPS and a communication facility compatible with ADS-B (Automatic Dependent Surveillance Broadcasting).

In contrast, the *Air/Ground Distributed approach* (Reference 12),as advocated by the PHARE consortium, aims at "*freezing*" a 4 dimensional volume of airspace around an optimum trajectory. This trajectory is the result of a machine-to-machine negotiation process that ensures a conflict free path for a given period of time, say 20 minutes. It is required that each aircraft is equipped with an advanced flight management system that is capable of keeping the aircraft with high accuracy within the agreed 4 dimensional "tube". A high performance air-ground datalink is a pre-requisite.

Considerably more simple is the *dynamic planning of the traffic over multiple sectors* based on the Zone of Convergence concept (Reference 13). Following this approach, the automation performs sequencing and scheduling at all points where traffic converges. Subsequently it compares the actual progress of the flights against optimum flight profiles. The system generates speed control advisories if a subject aircraft appears to be outside a "Region of Conformance". The dimensions of the "cocoon" represent the remaining flight profile control capabilities with respect to the constraints at the specific convergence point. The system is dynamic in that the traffic situation and advisories are continuously re-assessed when new position data become available. In this way, the "system plan" is automatically updated following the controller's decisions.

Autonomous Flight is the extension of the Free Flight concept to all phases of flight, so including operation in the Terminal Areas. No active control by the ground will exist anymore except maybe for ground operations. In effect this is the "engineers' dream".

6. Benefits of automation

In a "low" to "medium" density sector one experienced executive controller can perform all tasks required to ensure a safe and expeditious flow of traffic through his/her sector. When the traffic density increases, the number of potential conflicts increases exponentially and a planning controller is added. The planning controller searches for potential conflicts on the basis of flight profile data predicted by the Flight Data Processing System. If, on the basis of a set of criteria, a potential conflict is detected, the planning controller tries to modify the transit conditions of the flight, in particular the entry and exit levels. This will lead to a reduction in potential conflicts for the executive controller, but this is achieved at the cost of *less optimal flight profiles* for those aircraft that are affected.

Present high computing power, good aircraft performance data, accurate environmental data (e.g. weather, winds, airspace management constraints) and a knowledge of the flightcrew intentions (through updated flight plan data) will permit accurate trajectory prediction data to be produced. Hence automated assistance can be provided throughout the decision making loop :

- flight path prediction will permit *early detection of potential problems* such as aircraft/aircraft conflicts or aircraft/airspace infringements. A given controller usually knows the traffic he/she controls, plus the aircraft due to enter his/her area of responsibility in the next few minutes. The "*system*" has knowledge of the whole traffic. Through the use of multi-sector planning, "*smoother*" problem resolution will be possible, reducing the amount of instructions to be delivered by the executive controller

and sharing the remaining ones over the total workforce;

- appropriate algorithms will permit some filtering between *"problem"* and *"non-problem"* traffic, thereby *reducing the controller's mental workload* by minimizing the number of variables to be considered for predicting the future ;

- intelligent software mechanisms, using a trial generator (*"What-if"*) approach, will help resolving problems by computing the *"Best Next Clearance"* to be delivered to the flight. The overall problem density will be reduced, and therefore the volume of amendments to be communicated to the flightcrew will be kept to a minimum. This Best Next Clearance will be reassessed regularly/continuously and corrections will be provided if necessary.

Ultimately, an overall *reduction of the situation complexity* will be achieved, and the controller's situation awareness will be reinforced. By providing controllers with automated assistance, the use of trajectory prediction derived functions will be the way to cope with the increase in the traffic expected for the coming years, while maintaining a high degree of safety and efficiency.

7. Safety risks of automation

7.1 Contingencies

When automation is introduced in the safety critical path of a process, it is paramount that the correct operation of the tools is ensured at all times. For example, on board of a commercial aircraft the auto pilot function is often tripled. The three systems used are of a different design and use different sensors where possible.

In ATC systems the situation is different. The basic input data for the automated tools consists of the *current system* plan and *radar track information.* In this context the predicted trajectories constitute only processed information, i.e., the integration over look-ahead time of the information contained in the system plan. This holds that it is very difficult to ensure or check the consistency between the strategy in the mind of the controller, the information contained in the system plan and the plan executed in the flight management system of the aircraft.

The safety risks introduced by automation depend to a large extent on the increase in capacity that is achieved by its functionality when it is working properly. For each automated tool introduced it needs to be investigated what the safety risks are for the following three contingency cases:

1. The controller is aware that the tool does not work;
2. The tool does not work but the controller is not aware of its malfunctioning;
3. The tool works but generates wrong information for one or more flights.

How can a controller be sure that the information provided is generated correctly, or worse, if a warning function is operating correctly? In this respect it is clear, that the more intelligent the tools are, the higher the information content that they produce will be, but also the more difficult it is for the controllers to identify any malfunctioning. Accordingly, monitoring the correct operation of the tools could result in a *considerable workload,* typically in high density situations when the tools are relied on the most.

7.2 Categories of safety risks

On the basis of the type of information generated, the automated tools in ATC can be divided into two categories, namely:

Category A: *Tools that summarize certain characteristics of the traffic situation*: These include the "radar window", the "Conflict and Risk Display (CARD), the co-operative tools (ERATO), the Horizontal and Vertical Aid windows, etc.

Category B: *Tools that generate advisories*: Examples include Monitoring Aids, Departure and Arrivals Management Aids, Conflict Resolution Aids, etc. These tools try to enhance the correlation between the flight profiles predicted by the Flight Data processing System and those actually flown. Although the information generated only consists of "advisories", it is quite understandable that, after some time, controllers will follow them more or less automatically. This category can be sub-divided in function of the information content of the advisories, namely:

(1) times or a traffic sequence over a fix:

Advisories of this category affect the global flow characteristics of the traffic. They are the least dangerous and it is relatively easy to detect if they are incorrect.

(2) speed advisories:

If advisories of this category are incorrect, conflict situations could develop, but relatively slowly.

(3) advisories containing a change in heading and/or altitude:

If these advisories are incorrect, the risk of a conflict can be *imminent.* Advisories of this category are risky and can only be presented to the controllers after careful checking by an independent validation function.

7.3 Back-up functions

Fortunately, in the Air Traffic Control system two back-up functions are available as a safety net. In the first place, the Short Term Conflict Alert function tries to detect potential conflict situations within a look-ahead time of about 2 minutes. Its "sensor" data are the radar track information and therefore are independent from the system plans in the Flight Data Processing System. Secondly, in the future a large number of aircraft will be equipped with TCAS facility. In case that the ground system fails to detect and resolve a conflict situation in time, the pilots of the aircraft concerned will be alerted.

The discussion on the safety aspects of the interface between TCAS alerts and the Air Traffic Control system are outside the scope of this paper. This also applies to the tools that perform trajectory negotiation between the air and the ground systems as proposed in certain air/ground distributed concepts.

8. Automated tools

8.1 Filtering tools

The filtering of problem/non-problem traffic can reduce the workload of the controller team considerably. The more intelligent the implemented filtering algorithms are the more efficient the function will be. However, the efficiency reduces rapidly in complex situations. Moreover, safety might become a problem as the risk of unexpected events increases when a combination of unforeseen situations occurs and, as a consequence, one aircraft too many is filtered out.

8.2 Medium Term Conflict Detection tools

Most Medium Term Detection tools have a target look-ahead time of 20 to 30 minutes. Due to the uncertainties associated with "open-loop" trajectory predictors, the information presented to the controller team for look-ahead times of 15 minutes or greater is more at the level of the filtering tool described above. For look-ahead times below 4 minutes it is similar to the information generated by the Short Term Conflict Alert tools. For look-ahead times between 4 and 15 minutes, the reliability of the information presented depends largely on the level of correlation that can be ensured between the predicted and actually flown flight profiles. The controller team will need to carefully monitor the correct operation of the tool else dangerous situations could develop rapidly.

8.3 Monitoring tools

An example is the Monitoring Aid, MONA, function in the EATCHIP III system. MONA monitors the evolution of the flight and "reminds" the controller of a planned action, e.g. to change heading or level, etc.

8.4 Departures and Arrivals Management tools

Depending on the complexity of the tool, it could generate all three categories of advisories, i.e. the optimum landing sequence and target times over certain fixes, the best speed profile to meet these constraints and heading advisories in the TMA to actually build the sequence.

9. Moving the capacity barrier

With today's level of technology only human-centered automation techniques can be applied. The major tasks to be performed by the controller team in a sector consists of standard communication, monitoring of the traffic situation, prediction the future evolution of the traffic and detection of potential conflict situations and their resolution. The relation of these tasks is depicted in Figure 4. Although the relative workload values presented are only indicative, Figure 4 highlights that the workload associated with basic communications, monitoring and the prediction of the future evolution is close to a linear function of the number of aircraft in the sector. However, when the traffic includes potential conflicts, the workload increases exponentially. Indeed, it has been often observed in real-time simulations that even a small increase of e.g. 2% in traffic density can, change the working atmosphere from *relaxed* to *hectic* (Reference 14).

When the traffic enters a sector in nicely organized continuous streams and there are no particular exit constraints, the capacity barrier is met at a considerable higher number of aircraft in the sector than when aircraft are entering randomly. Therefore when automation tools are introduced in a human-centered ATM concept they should

- primarily aim at *smoothing the traffic flows*, and,
- generate information for the controller team that is *not safety critical.*

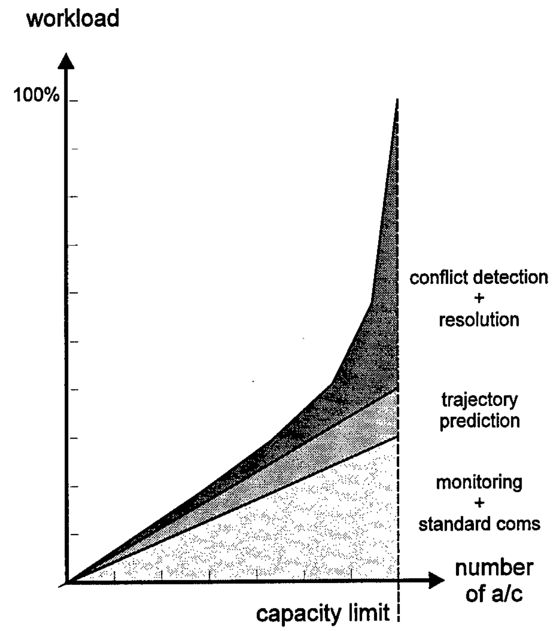

Figure 4 Controller workload

It has been shown in Reference 13 how, when planning the traffic flows over more than one sector using speed control possibly enhanced with an associated adaptation of cruise levels, can achieve this very efficiently.

10. Human resources

A considerable amount of work has been done by Human Factors specialists (Reference 15) studying vulnerabilities in flightcrew management of automation, in particular:

- Pilot understanding of automation's capabilities, limitations, modes, operating principles and techniques. "Surprises" where automation behaved in ways the flightcrew did not expect, lead to remarks like "*Why did it do that*?", "*What is it doing now*?" and "*What will it do next*?".
- Potential mismatches between the designers assumptions on how the flightcrew will use the automation and the reality.

Today, in most countries of the European "core "area, the minimum initial education level required to be admitted to the training for Air Traffic Controller is a High School certificate (Baccalaureate). Nevertheless, to succeed the training additional, special skills are required as the rate of recruitment success is below 10%. Moreover it may be expected, as was the case for flightcrews earlier, that with the introduction of automation, the skill level of the air traffic controllers needs to be enhanced. Indeed, in the future system, they will also need to be capable of working with the automated tools and monitoring their correct operation.

It can be expected that this increase in controller responsibilities and required capabilities will make it more difficult to find controllers that can match the required performance. The enhancement of the future responsibilities must considered already today when defining the selection criteria for being admitted to a training for Air Traffic Controller. In addition, it must be expected that a number of controllers presently in active duty will have difficulties in adapting to the new working environment and therefore need to be promoted.

11. Will it work?

Despite all theoretical studies and dedicated demonstrations still the question remains if the introduction of a tool or a concept indeed brings the practical advantages that were envisaged at its conception stage. Will the reduction in controller workload due to information generated by the tool not offset by the workload required to perceive the information, checking its validity and the monitoring of the correct operation of the tool?

From the past we know of several strategies that performed beautifully as engineering prototypes but failed partly or sometimes completely when exposed to a more realistic ATC environment. (Reference 10). In was found that the major reason most often was that the automated tool was limited to a reduced set of possible solutions whereas the controllers, when working without the tools, better used their imagination. Often controllers found globally better solutions be it at the cost of sometimes very high workload which was difficult to sustain over an extended period of time. In general, the safety aspects could not really be assessed.

Where large scale, real time simulations were very successful in validating new airspace organizations and coordination procedures, they seldom lead to clear conclusions in "study" simulations. Typical problem areas are: insufficient time for the controllers to train with the new tools in the specific operational environment as it is often different from their normal working one, and, a technical simulation environment which is not really capable of supporting the technology required by the new tools, e.g. response times, reliability of computed flight profiles, stability of the air system, etc. So new ways are required.

12. The EATCHIP demonstration programme

The EATCHIP III demonstration programme brings the prototypes of HMI components and advanced ATM functions to the control centres in the member states. Local controllers can have hands-on experience

with the proposed facilities and discuss the *why's* and *why not's*. In this way a large percentage of the active control community can be reached providing the feed-back required to keep the system designers with their feet on the ground.

This demonstration programme is facilitated by a small scale, real-time simulation platform that is designed and maintained by the Rapid Prototyping Facility in Eurocontrol Headquarters (Reference 16). Special attention is given to human-machine interface aspects and the simulation of system failures. The simulator can be implemented on generic Unix platforms. Tested versions exist for Silicon Graphics, DEC-Alpha, HP, Data General, SUN and Intel platforms (PCs) running Linux or Solaris. The software is freely available for use by the ECAC member states and to industry for evaluation purposes. At the time of writing this simulator has been installed in nine member states.

13. Conclusions

Today in certain instances, the capacity barrier has been reached. This results in increasing delays, cost and frustration. The EATCHIP programme of Eurocontrol, in close cooperation with its member states is defining the EATCHIP Phase III ATC system generation that aims at improving ATC *capacity* and flight *economy* whilst at least maintaining the present *safety* level. It intends to achieve this by introducing automation in a *human-centered* approach. This approach means that humans decide and machines support.

The paper highlights some of the human characteristics that affect the capacity and safety aspects. It indicates safety risks depending on the type of supporting information that is generated by automation.

There are indications that, when organizing the traffic flows over more than one sector using speed control, possibly enhanced with an associated adaptation of cruise levels, an optimum symbiosis between humans and machines can be achieved without compromising safety.

An adequate training programme of the present controller community is required to provide them with sufficient skills to work with the automated tools and to perform the monitoring of their correct operation. Possibly this may also affect the selection criteria of new controllers.

In order to get feedback on the applicability of the concepts developed they need to be exposed to the active controller community. The EATCHIP demonstration programme is a positive step in the right direction.

Unfortunately full automation as applied in the Autonomous Flight concept is still some time away.

The best thing about the future is that it comes only one day at a time.

- Abraham Lincoln

14. Disclaimer

The opinions expressed in this paper are those of the authors. The paper is disseminated under EUROCONTROL's sponsorship in the interest of information exchange. EUROCONTROL assumes no liability for the contents or use thereof.

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OPTIMIZATION TECHNIQUES AS AVAILABLE FOR ON-LINE OPERATIONS

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1. INTRODUCTION

In the frame of this workshop dedicated on support for decision making optimization and automation, it appeared useful to the organizing team to include a general presentation of what optimization means and of the various existing methods to solve optimization problems.

In this paper we will try to classify the optimization techniques according to the type of problems they are intended to solve and to the type of solutions that may be expected for each of them.

We do not pretend to any exhaustiveness since our concern is more to describe the wide methods families.

In fact many methods exist. For all types of methods, adaptations, improvements have been developed in order to increase their efficiency, their rate of convergence or decrease computing time. For specific applications, the best results are often obtained from the combination of several algorithms. In taking advantage of the specificity of each, efficient methods are then obtained.

2. OPTIMIZATION PROBLEM STATEMENT

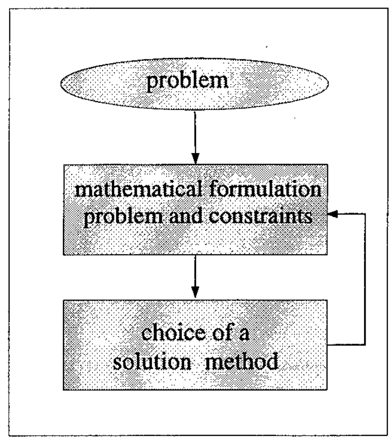
The choice of the "best" solving method among all existing depends on the way the problem is settled. The formulation of the mathematical optimization problem results from the following three steps:

- problem analysis

- mathematical statement or modelling of the system, of the objective function and of the constraints.

- choice of a solving method.

The process is thus as indicated in the figure.



Analysis

Analysis and formulation of the problem are the key points in any attempt of optimization of a system. One's has to carefully analyze the problem in detail in order to clearly identify his objectives, the parameters and the associated constraints, with their degree of importance.

Modelling

The purpose of modelling is to give a mathematical representation of the problem, that has been identified, that is to give a model of the system and to specify the parameters to optimize. The objective function should also find a mathematical formulation reflecting as well as possible the required objectives.

Choice of a solution method

The last step is the choice of an adequate method for solving the mathematical statement of the optimization problem.

In practice the statement and the modelling of the problem are tightly related with the solving method. It is clear that the mathematical formulation of a real problem is not unique. It always results from approximations, simplifications, even linearizations or discretizations.

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The domains of variation of the variables, for example continuous or discrete, may also result from a choice in the modelling process; for some problems the domain of variation of the variables is naturally discrete, for other problems some variables may be or not discretized.

Another aspect of the multiplicity of modelling for a real problem is the fact that in a real problem, objective function and constraints are not clearly distinct. So in practice the modelling may be the result of an examination of the existing methods and an adaptation to them. If the implementation of the solving method turns out to be too tricky, a new formulation of the problem may be necessary.

In other cases, from the examination of the obtained solution, it may be concluded that it doesn't fit with the original intentions, and then the problem has to be reexamined, the objectives and constraints restated.

This iterative process between formulation-modelling and solution is represented in the figure by the feedback arrow.

The process is thus as indicated in the figure.

3. CLASSIFICATION OF OPTIMIZATION METHODS

This section presents a attempt of classifying the existing methods according to the type of problems they may solve, and to the domain of variation of variables.

Static problems

The problem being:

Find x which minimizes the objective function $J(x)$

with constraints $x \in D$,

we adopt the following classification according to what x, $J(x)$ and D are.

In the case where the x variables are continuous:

nonlinear programming, steepest descent type methods,

linear programming.

In the case where the x variables are discontinuous or discrete: combinatorial optimization

integer linear programming,

Branch and bound,

CSP : constraint programming.

New methods

apply for any kind of variables, and for the same kind of

problems,

neuronal methods,

genetic algorithms,

simulated annealing.

Dynamic problems

It is the case where the system equations are dynamic:

$$\dot{x} = f(x, u, t)$$

for continuous systems, or

$$x_{n+1} = f\left(x_n, u_n, n\right)$$

for discrete systems.

In that case the problem is to find the control $u(t)$ or u_n that minimizes the objective function:

$$J(x, u, t)$$

in the continuous case or

$$J\left(x_n, u_n, n\right)$$

in the discrete case

variational methods, maximum principle,

with particular case of singular perturbations,

and dynamic programming.

4. STATIC PROBLEMS IN CONTINUOUS DOMAIN

4.1 Linear programming

This method applies to problems in which the objective function is a linear function of the variables to optimize, with linear inequality constraints:

minimize $f^T x$

subject to $Ax \geq b$

and $x \geq 0$.

It can be shown that it is always possible to put the problem in the following canonical form:

minimize $g^T y$

subject to $By = c$

and $y \geq 0$.

The solution is obtained through very well known *simplex* method. It is based on the fact that the objective function assumes its minimum at an extreme point of the convex polyhedron generated by the set of the feasible solutions of the problems, that is all the solutions of $By = c$ and $y \geq 0$.

The obtained solution, when it exists, is the exact solution of the problem.

The algorithm is the following:

- find a feasible solution,
- test for optimality of this solution,
- if the solution is not optimal, select another solution corresponding to a lower value of the objective function.

- test again for optimality and so on ....

We may then interpret the simplex procedure in terms of moving from one extreme point to an adjacent extreme point, until the minimum is obtained.

Other approaches exist to linear programming such as interior point methods.

In [7], linear programming is used in conjunction with heuristics to manage airlift operations. The number of crew involved in the airlift is minimized, by computing the arrival times of aircraft on legs and the connections of crews.

The problem of assigning aircraft to gates in order to minimize the walking distance for passengers is stated and solved in [5] in terms of linear programming, with addition of heuristics.

Linear programming is also used to solve the ground holding policy problem in [6] : The ground delays are there optimized by minimization of total expected delays cost.

4.2 Nonlinear programming

The field of nonlinear programming includes all methods enabling to find the minimum of a nonlinear objective function, subject to nonlinear constraints.

The general problem of mathematical programming may be stated as:

Find the vector x which minimizes the nonlinear function $J(x)$

subject to the nonlinear inequations:

$g_i(x) \leq 0 \qquad \text{for} \quad i = 1, m.$

Many computational algorithms exist for solving this problem, and we limit the description to the general principle of the most current ones.

One of the main difficulties encountered is the determination of a global optimum, that is a solution which optimizes the objective function over the complete range of the solution space.

Obtention of the global optimum may only be guaranteed for convex-programming problems, that is problems in which both objective function and constraints are convex.

The different techniques rely on the optimality conditions, which are:

$$J_x(x) = 0 \qquad \text{and}$$
$$J_{xx}(x) \qquad \text{positive}$$

, where $J_x(x)$ denotes the vector of partial derivatives (gradient) of J with respect to the x variables and $J_{xx}(x)$ is the Hessian matrix, that is the matrix of the 2nd order derivatives. The first condition is the necessary condition for a local extremum, and the second is a sufficient condition for a relative minimum.

We consider hereafter the case where the optimal solution cannot be obtained explicitly, and where the solution is computed by an iterative process.

4.2.1 Gradient or Steepest Descent Method

Let x_i be a solution at iteration i, and define

$$\Delta J = J\left(x_{i+1}\right) - J\left(x_i\right)$$

Since

$$J\left(x_i + \delta x\right) \approx J\left(x_i\right) + J_x^t\left(x_i\right)\delta x$$

for $|\delta x| \leq \epsilon$ we may write

$$\Delta J \approx J_x^t\left(x_i\right)\delta x$$

Thus δx with bounded norm that maximizes $-\Delta J$ is the vector with norm ϵ and colinear to $J_x^t(x_i)$.

Since ϵ is not known, the algorithm uses the iterative formula:

$$x_{i+1} = x_i - k J_x\left(x_i\right)$$

where k is a parameter of the algorithm, fixed or decreasing with i.

We may interpret this procedure in terms of moving in the tangent plane to the objective function, in the direction of steepest descent.

4.2.2 Newton's method

This method is derived from the iterative Newton Raphson method for solving a nonlinear equation

$$g(x) = 0$$

The solution at step *i+1* is computed from:

$$x_{i+1} = x_i - k G_x^{-1} g\left(x_i\right)$$

where G_x is the matrix with elements $\frac{\partial g_i}{\partial x_j}$. The next point *i+1* is the intersection of the curve tangent at point *i* with x axis (when *k*=1).

The stationarity equation for the objective function

$$J_x(x) = 0$$

is solved using this method and the scheme is then as follows:

$$x_{i+1} = x_i - k J_{xx}^{-1} J_x\left(x_i\right)$$

Taking into consideration the second order development of the objective function at point x_i:

$$J\left(x_i + \delta x\right) = J\left(x_i\right) + J_x^t\left(x_i\right)\delta x + \frac{1}{2}\delta x^t J_{xx}\left(x_i\right)\delta x$$

we may observe that the value of δx which minimizes this quadratic expression is given by:

$$\delta x = -J_{xx}^{-1}\left(x_i\right) J_x\left(x_i\right)$$

4.2.3 Implementation

The equality constraints are taken into account by introduction of the Lagrangian multipliers, which increase considerably the complexity of the algorithm. Another way of taking the constraints into consideration is to express them as penalty functions added to the objective function.

The inequality constraints may always be expressed as equality constraints, by adding fictitious supplementary variables.

Convergence of these algorithms depends of course on the choice of parameter k in the iterative process, and on the initial point. Generally speaking, the rate of convergence of gradient type methods is very low. The convergence properties of the Newton's Method are better, but it requires the inversion of the Hessian matrix J_{xx}, which increases complexity of the computations at each iteration.

Numerous methods have thus been developed, trying to increase the convergence of the Gradient method and to avoid inversion of Hessian matrix.

As mentioned before, the minimum obtained is a local exact minimum. Global optimality requires a convex objective function.

The Lagrangian multipliers are often used to split large problems in several smaller ones. For instance, in the case of temporary closure of airports re-scheduling of the flights was performed by maximization of system profit with respect to flows in flight arcs. The Lagrangian multipliers, updated by a gradient algorithm, are used to coordinate several subproblems solved by the simplex method.[10]

5. DISCRETE DOMAIN - COMBINATORIAL PROBLEMS

We include in this section all methods suitable for solving static optimization problems in which the variables belong to a finite discrete set.

One of these methods is integer linear programming, which gives the exact solution of a minimization problem with linear objective function and constraints, in the case of discrete domains of variation for variables.

Besides this method, we present below Branch and Bound and CSP.

5.1 Branch and Bound

In order to find the optimal solution, in terms of an objective function, among a finite set of feasible solutions, the principle of this method is to part (or "*branch*") the set of solutions in smaller subsets, and to evaluate a lower "*bound*" of the objective function for all solutions of the subset. The process is repeated until obtention of the optimal solution,

Implementation of the method relies on the definition of a separation principle for the solutions, and on the evaluation of a lower bound of the objective function.

This evaluation of course should not require to detail all solutions of the subset, but should result of an analysis of the common characteristics of them.

The subsets of solutions have a treelike structure, and the algorithm for moving in this tree is as follows:

After partition of the current subset in smaller subsets and evaluation of the lower bound of the objective function for each of them, all endpoints evaluated so far are considered and the algorithm starts from the point with smaller lower bound.

The process is repeated until obtention of a single solution subset, with a objective function below all bounds. This solution is then the optimum solution, since all other solutions correspond to higher valued objective functions.

The efficiency of the method, that is the number of evaluated nodes, relies on the relevance of both separation and evaluation principles. No general method exists for determining them, and they should result from a fine analysis of the problem.

This method guarantees obtention of the exact optimal solution, but it doesn't guarantee the number of steps. In the worst case, the solution may be obtained after complete examination of the tree.

We may mention two applications of this algorithm. The first one is again the on-line assignment of aircraft to gates in order to minimize the walking distance for passengers [2]. This example highlights the fact that the same problem may be stated in diverse forms, leading to different solution methods.

The second one is the real time scheduling of landing sequence of aircraft. The objective function to be minimized is the operating cost, and the variables are the sequence of aircraft and their descent speed [3].

5.2 CSP (Constraints Satisfaction Problems)

The purpose of CSP algorithms is to solve discrete constraints satisfaction problems. The main idea is to use the constraints to limit the search space of solutions through constraints propagation algorithms. This propagation iteratively reduces the domain of variation of variables.

Resolution mechanisms and, among them, constraints propagation principles which are implemented in the various Constraints Programming Languages (CPL), all rely on the same concepts.

The resolution consists in 2 steps:

– an *a priori constraints propagation phase*, which reduces through a filtering algorithm the domain of variables. After this step threes cases are possible:

- failure if one or more constraints cannot be satisfied, which means that the problem has no solution.

- obtention of the solution if all variables are instantiated, i.e. they can only take one value.

- some of the variables are not instantiated, and in that case a solution is derived from the generation phase.

– the *generation phase* making use of "choice and propagation" type methods.

Those methods, dedicated to constraints satisfaction problems may be used for solving optimization problems, by use of the following mechanism:

– In a first step the constraints satisfaction problem is solved.

– The objective function of the obtained solution is then computed.

– A new constraint is then added to the problem, expressing that the objective function should be less than this value.

– and so on until obtention of a satisfactory solution.

6. NEW METHODS

By "new" methods, we mean a series of methods that have developed recently, due to the tremendous increase of computing power. Those methods are rather general and enable to solve a variety of problems.

We present here the simulated annealing, the neural methods and the genetic algorithms.

Simulated annealing and genetic algorithms are stochastic methods. The part of random search that they include implies that the obtained solution is not the exact optimal solution to the problem. But they provide a set of "good" solutions.

6.1 Simulated Annealing

This method relies on the analogy with the physical process of materials annealing. The process consists in bringing the solid to very high temperature up to fusion, and in cooling it slowly, with a specific temperature profile, which enables it to reach a minimum energy solid state.

The simulated annealing algorithm, as applied to an optimization problem, is derived from this process with analogy between solid energy and objective function.

It is an iterative algorithm as described below:

Let J_i be the current value of the objective function at iteration i and x_i the value of the variables.

Let a new value of x, x_{new}, be chosen *at random and in the vicinity* of x_i, and let J_{new} be the corresponding value of the objective function.

- If $J_{new} < J_i$,

transition is accepted and the new value of state is $x_{i+1} = x_{new}$,

- If $J_{new} \geq J_i$,

transition is accepted with the probability

$$p = e^{-\Delta J/T}$$

where T is the simulated annealing temperature. In the case where the transition is accepted, the new value os state is: $x_{i+1} = x_{new}$, otherwise another value for x_{new} is tried.

The temperature is chosen such that the transitions corresponding to a high worsening of the objective function are accepted at beginning of the algorithm, so that the whole state space is explored. After a while, the temperature decreases so that less and less objective function worsening are accepted.

The parameters to be adjusted are:

– the temperature variation, that is its initial value and its profile,

– the definition of *vicinity* of a state, in which next point is randomly chosen,

– the criterion for ending the procedure.

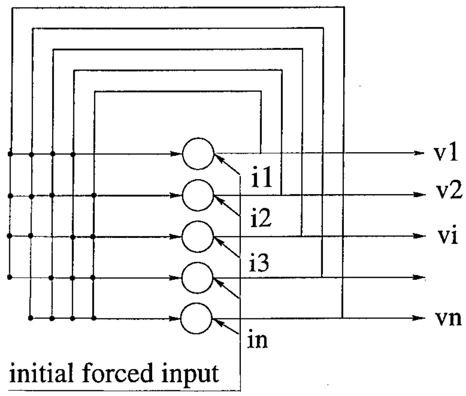
Initial temperature is usually set such that initial probability is equal to 0.5, for an acceptable ΔJ and the temperature profile is often made of several levels.

Convergence of the algorithm to the absolute optimum may be established in ideal conditions (finite state space, infinitely slowly decreasing temperature). From a practical point of view, the method usually efficiently leads to a neighborhood of the solution.

6.2 Neuronal Methods

Neuronal techniques enable construction, through examples, of classifiers which have the ability to recognize the membership class of a pattern, after a learning phase where examples with their membership have been presented to the neural network. This kind of neuronal model is used in 90% of the presently known applications.

But other models have been elaborated in order to perform other functions with neuronal networks. As an example we present here the Hopfield network. It is a recursive and completely connected network with a feedback of the output to the input. It may assimilate to a dynamic system with N possible states. Among them, p are stable, and initial states may be split into *attraction fields*, in which all states lead to the same stable state. When functioning the network looks for those attraction states, which correspond to local minima when the network is used for minimization.



Hopfield Network

The network state is the state of the n cells. The rule for ith cell state change is as follows:

$$
\begin{aligned}
V_i(t+1) &= 1 && \text{if} \quad u_i(t) > 0 \\
V_i(t+1) &= V_i(t) && \text{if} \quad u_i(t) = 0 \\
V_i(t+1) &= 0 && \text{if} \quad u_i(t) < 0
\end{aligned}
$$

with:

$$u_i(t) = \Sigma_{j=1}^{n} W_{ij} V_j - I_i$$

The Hopfield network is convergent, that means that whatever the starting point, it moves towards an attraction point. So there exists a Lyapunov function, which is bounded and decreases along the system trajectories. It is called Hopfield energy:

$$E = -\frac{1}{2}\Sigma_{j=1}^{n} \Sigma_{j=1}^{n} W_{ij} V_i V_j + \Sigma_{j=1}^{n} V_i I_i$$

So for this network the synaptic weights are not learned, but computed from the function to minimize.

Hopfield solved the salesman problem with this network, but we must admit that, besides that, this technique is not commonly used.

6.3 Genetic Algorithms

The genetic algorithms perform an iterative search of optimum, by improvement at each iteration of the set of the solutions, and by complementation with randomly generated solutions.

The vocabulary is derived from human genetics. The successive iterations constitute the “generations”, a solution is an "individual", and the set of solutions is the “population”.

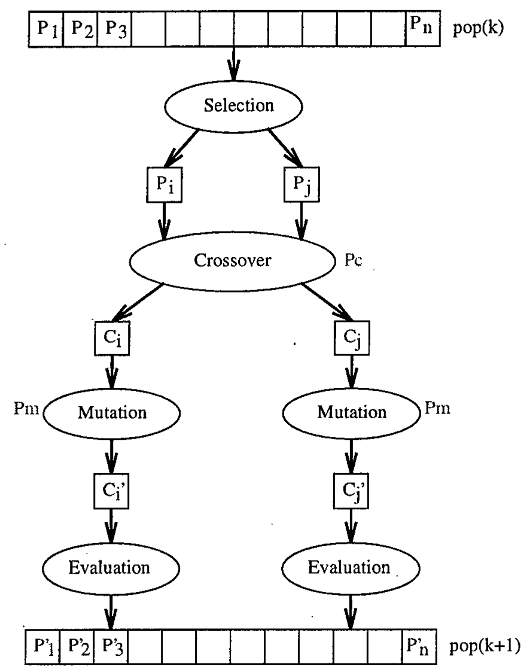
The principle is depicted at the figure below.

Let consider the population of ith generation. A solution is represented by an informatic code called “chromosome”. The mechanism of production of the population of generation i+1 consists of three steps, the selection, the crossover and the mutation.

Two individuals or “parents” are *selected* in the population, P_i and P_j.

A *crossover* operator is applied to those parents, which results in two children C_i and C_j. This operation aims to improve the existing solutions,

A *mutation* operator is then applied to those two children, which randomly produces two new children C_i' and C_j'. Crossover and mutation operators are applied with respective probabilities p_c and p_m. Randomly generated individuals are produced,and this operation guarantees that the whole solution space is explored. The value of the objective function, called here “*fitness*”, of those new solutions is assessed and decision may be taken to include them in the new population.



Genetic Algorithms Principle

Several parameters have to be settled to implement a genetic algorithm:

- the size of the population,

- the choice of the initial population,

- the solution coding (bits or real codes),

- the choice of the selection algorithm with associated probability,

- the choice of the crossover process, that is the mechanism itself and associated probability,

- the choice of the mutation process, that is also the mechanism itself with the probability,

– the number of generations to create before stopping the algorithm.

The number of choices is rather wide and the quality of convergence of the algorithm of course depends on those choices.

Some results exist concerning asymptotic convergence, but from a practical point of view, the algorithm is usually stopped after a predefined number of generations. The optimal solution is then not obtained, but at the end of the algorithm, several "good" solutions are available.

7. DYNAMIC PROBLEMS

In the dynamic problems, the system evolution is described by a differential equation:

$$\frac{dx}{dt} = f(x,u,t)$$

with initial conditions

$$x(t_0) = x_0$$

Let u be the vector of variables to optimize. Those variables usually are the control variables for the system.

The objective function to be minimized is function of x, u, and may or not depend on time t.

$$J = J(x,u,t)$$

It is often expressed as an integral over a time period.

Final time may be set or not. The final state may be free, partly or completely set.

Time itself is the objective function in the particular case of minimum time.

7.1 General case

Due to the multiplicity of possible formulations, it is difficult to give a general solution method.

Generally speaking we may note that the solution is obtained through calculus of variations or maximum principle.

This class of problems includes trajectory optimization and optimal control. Depending on the problem, the obtained solution is an "open loop" solution

$$u^* = u(t)$$

or a "closed loop" solution

$$u^* = g(x,t)$$

It may or not be possible to express an explicit solution. In the case where an explicit expression is not available, numerical methods have to be used to solve the optimality equations.

Two special cases may be pointed out. The first one is the *singular perturbations* method. It applies to systems containing dynamics with multiple time scales. In that case it is possible to simplify the resolution process taking this fact into account.

The second case is dynamic programming described in the next paragraph.

7.2 Dynamic programming

We consider here dynamic systems with time discretization. Let x_n be the state at time n and u_n be the control vector applied at time n.

The system evolution is described by the discrete state equation:

$$x_{n+1} = f\left(x_n, u_n, n\right)$$

To the u_n control that leads the system from state x_n to state x_{n+1} correspond the elementary income

$$r_n = r\left(x_n, u_n, n\right)$$

The optimization problem consists in determining the successive values of control u_n, which lead the system at final time T, in a fixed state or partially fixed state, with a minimum value of the objective function:

$$R_0 = \Sigma_0^{N-1} r_n$$

The basis for dynamic programming is what Bellman refers to as the *principle of optimality.* It may be summarized as:

Any part of an optimal trajectory is optimal.

From this principle, recurrence relations for the objective function may be derived, in two forms, an inverse expression and a direct expression.

Inverse expression

Let $R^*(x_n, n)$ be the optimal income of the problem starting at time n with initial state x_n. From optimality principle we may derive:

$$R^*\left(x_n, n\right) = opt$$
$$r\left(x_n, u_n, n\right) + R^*\left(f\left(x_n, u_n, n\right), n+1\right)$$

where optimization is carried out with respect to the u_n vector.

In the case where the final time N is fixed, resolution starts from this last time. If the final state is unconstrained, the first relation to consider is:

$R^*(x_N, N) = 0.$

Otherwise, k of the final control variables from u_{N-1} to u_{N-k} are not free, and $R^*\left(x_{N-k}, N-k\right)$ is determined.

The problem is then solved backward, until initial time.

Direct expression

Let $R^*(x_n, n)$ be the optimal income of the problem starting at time 0 and ending at time n with state x_n. From optimality principle it may be derived:

$$R^*\left(x_n, n\right) = opt$$
$$r\left(x_{n-1}, u_{n-1}, n-1\right) + R^*\left(x_{n-1}, n-1\right)$$

where optimization is carried out with respect to both x_{n-1} and u_{n-1} vectors.

In this case we develop a forward solution, starting from initial value:

$$R^*\left(x_0, 0\right) = 0$$

The Dynamic Programming Method has been used to minimize the total expected delay cost by controlling ground delays for a single landing period [1], and for multiple landing periods in stochastic cases [8]. The need for optimization in that kind of problem relies on the fact that ground and air delays do not have the same costs.

Dynamic Programming is also used for computing shortest or quickest paths in a graph, besides other graph methods such as the Dijkstra algorithm. For example, rerouting based on Dijkstra algorithms have been proposed by J. Pararas (MIT). It is also used for the revision of flight plans in a network with the objective to minimize either total delays in arrival times or total increase in flight times [9]

8. CONCLUSION

In this paper we have tried to emphasize the great diversity of existing available methods for solving an optimization problem. Direct applications of those methods are presented in the workshop, showing the variety of the types of problems solved.

We would like again emphasize on the importance of the stage of formulating and modelling the problem, which not only directly affects the efficiency and the quality of the solution to the mathematical problem, but guarantees the adequation of the solution to the original real problem.

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OPTIMIZATION TECHNIQUES

AS AVAILABLE

FOR ON-LINE OPERATIONS

Nicole IMBERT
Jean - Loup FARGES

SUMMARY

Introduction: optimization problem statement

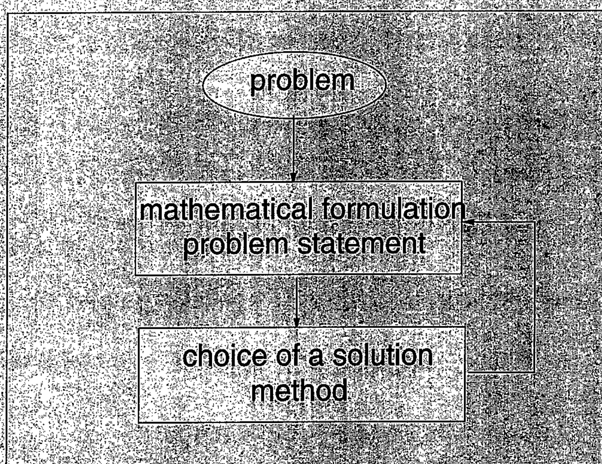
Classification of the methods

- static problems
- dynamic problems

Description of the various methods

Conclusion

OPTIMIZATION PROBLEM STATEMENT



AGARD BUDAPEST may 27th -29th 1997

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CLASSIFICATION OF THE METHODS

Static Problems

Problem: find x which minimizes the objective function

$I(x)$ with constraints $x \in D$

In the case the x variables are continuous:

- *non-linear programming: steepest descent type methods, Newton's method*
- *linear programming*

In the case the x variables are discontinuous or discrete:

- *integer linear programming*
- *Branch and bound*
- *CSP : constraint Programming*

New Methods

- *neuronal methods*
- *genetic algorithms*
- *simulated annealing*

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CLASSIFICATION OF THE METHODS

Dynamic Problems

In the case the system equations are dynamic:

$\dot{x} = f(x, u, t)$ $\qquad$ $x_{n+1} = f(x_n, u_n, n)$

problem: find the control

$u(t)$ or u_n

that minimizes the objective function:

$J(x, u, t)$ or $J(x_n, u_n, n)$

Methods

Variational methods, maximum principle

particular case of singular perturbations

Dynamic Programming

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Static problems- Continuous domain

LINEAR PROGRAMMING

In the case both objective function and constraints are linear

minimize $f^t x$		minimize	$g^t y$
subject to $Ax \geq b$	*equivalent to*	subject to	$By = c$
and $x \geq 0$			$y \geq 0$

SIMPLEX METHOD the minimum is at an extreme point of the polyhedron

Algorithm: find a feasible solution

test for optimality

if not select another solution with lower value of the objective function

test again for optimality and so on

$\Rightarrow$ ***Exact solution***

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Static problems - Continuous Domain

LINEAR PROGRAMMING

Examples of applications

- management of airlift operations
  - the minimum of crew involved in the airlift is minimizes
  - solution by simplex associated with heuristics
- assignment of gates (minimization of the walking distance for passengers)
- ground holding policy problem - optimization of the ground delays by minimization
  of total expected delays cost

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Static Problems - Continuous Domain

NON-LINEAR PROGRAMMING

Find the vector x which minimizes the nonlinear objective function $J(x)$

subject to the nonlinear inequations $g_i(x) \geq 0$ for $i = 1, m$

many formulations → many algorithms

all based on the optimality conditions

$J_x(x) = 0$ necessary condition for local extremum

$J_{xx}(x) > 0$ sufficient condition for relative minimum

main difficulty obtention of the ***global optimum***

guaranteed for convex-programming problems only

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Static problems - Nonlinear Programming

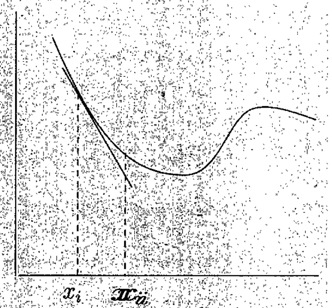
GRADIENT OR STEEPEST DESCENT METHOD

iterative method let x_i be solution at iteration i

and $\Delta J = J(x_{i+1}) - J(x_i)$

since $J(x_i + \delta x) \approx J(x_i) + J_x^t(x_i)\delta\varepsilon$

for $\mid \delta x \mid \leq \varepsilon$ $\Delta J \approx J_x^t(x_i)\delta x$



algorithm	$x_{i+1} = x_i - kJ_x(x_i)$

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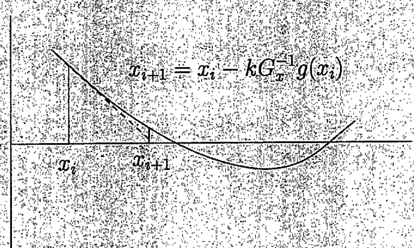
Static Problems- Nonlinear Programming

NEWTON'S METHOD

derived from iterative Newton Raphson method for solving $g(x) = 0$

$x_{i+1} = x_i - kG_x^{-1}g(x_i)$ with $G_x = (\frac{\partial gi}{\partial xj})$



used to solve stationarity equation $J_x(x) = 0$

$$\boxed{x_{i+1} = x_i - kJ_{xx}^{-1}J_x(x_i)}$$

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Static Problems - Nonlinear Programming
IMPLEMENTATION CONSIDERATIONS

Equality constraints taken into account by introducing **Lagrange Multipliers**

Inequality constraints taken into account by addition of variables

→ increase of the complexity

Convergence: gradient very slow

Newton's better but need for inversion of the Hessian Matrix

local minimum obtained - global only for convex problems

EXAMPLE rescheduling of flights in case of temporary closure of airports

maximisation of system profit with respect to flows

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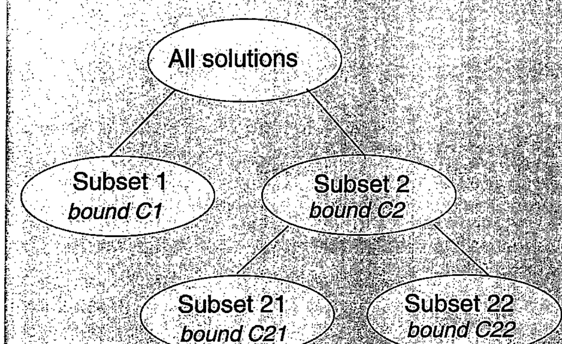
static problems - discrete domain
BRANCH AND BOUND



part into subsets (branch)

evaluate a lower bound of criterion

start from node with smaller value

until one element set with smallest value

Examples : Gate assignement for minimizing walking distance

Scheduling of landing sequences for minimum operating cost

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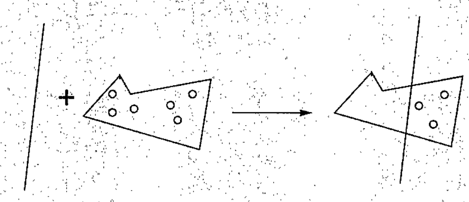
static problems - discrete domain

CONSTRAINTS SATISFACTION PROBLEMS

Main Idea : use the constraints to limit the search space
through constraints propagation algorithms

2 steps in most of CPL



- Constraints propagation phase

→ No solution

Single value: solution

Some variables not instanciated

↓

- Generation phase:

choice and propagation type methods

For optimization

New constraint: Criterion less than the value already obtained

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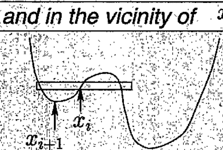
New Methods

SIMULATED ANNEALING

Analogy with the physical process of materials annealing

Iterative algorithm - at stage i x_i and J_i

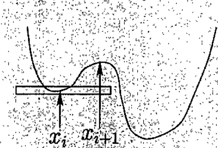
- chose x_{new} *at random and in the vicinity of* x_i



if $J_{xnew} < J_i$ then $x_{i+1} = x_{new}$

Otherwise the transition is accepted with probability

$$p = e^{-\Delta J/T}$$



T is the simulated annealing temperature, decreasing with i

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New Methods

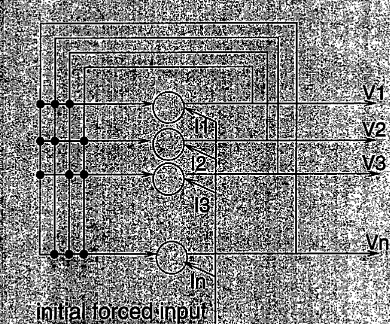
NEURONAL METHODS

$$\min_{V_i} \frac{1}{2}\{-\sum_{i=1}^{i=n}\{V_i I_i + \sum_{j=1}^{j=N} W_{ij} V_i V_j\}\}$$

cells change $V_i(t+1) = \begin{cases} 1 & \text{if } u_i(t) > 0 \\ V_i(t) & \text{if } u_i(t) = 0 \\ 0 & \text{if } u_i(t) < 0 \end{cases}$

with $u_i(t) = -I_i + \sum_{j=1}^{j=N} W_{ij} V_j(t)$

Hopfield network



Convergence towards one of the local minima

Salesman problem

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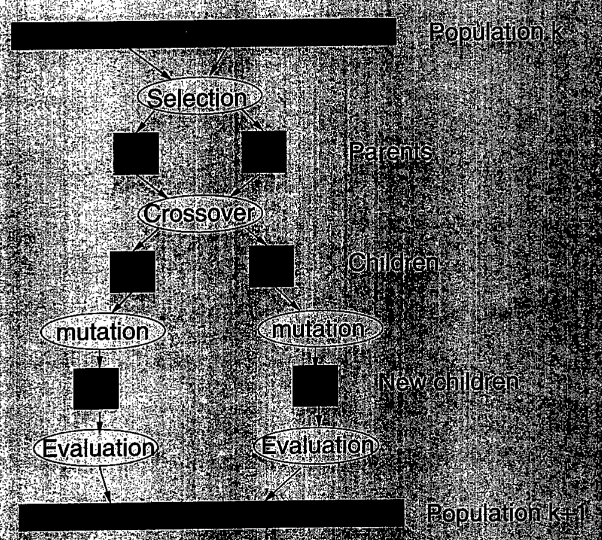
New Methods

GENETIC ALGORITHMS



Parameters

Initial population

Size of population

Coding

Selection method

Crossover method

Mutation method

Probabilities

Number of generations

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DYNAMIC PROBLEMS

General Problem

for the system $\dot{x} = f(x(t), u(t), t)$ with $x(t_0) = x_0$

$\min_{u(t)} J(x, u, t)$

Final time, final state: set or not

Often integral criterion

Calculus of variations - Maximum principle

Open loop solution $u^* = g(x_0, t)$

Closed loop solution $u^* = h(x(t), t)$

Dynamic problems - time discretization
DYNAMIC PROGRAMMING

Problem

$$x_{n+1} = f(x_n, u_n, n)$$

$$\min_{u_n} \sum_{n=1}^{n=N} r(x_n, u_n, n)$$

Principle of optimality: Any part of an optimal trajectory is optimal

Backward Dynamic Programming

$$R^*(x_n, n) = \min_{u_n}\{r(x_n, u_n, n) + R^*(f(x_n, u_n, n), n+1)\}$$

Also possible for stochastic problems (min of expectation)

Forward Dynamic Programming

$$R^*(x_n, n) = \min_{u_{n-1}, x_{n-1} / f(x_{n-1}, u_{n-1}, n) = x_n} \{r(x_{n-1}, u_{n-1}, n-1) + R^*(x_{n-1}, n-1)\}$$

EX : Minimization of total expected delay cost by controlling ground delay

CONCLUSION

Diversity of available methods

Variety of types of problems solved

Importance of the modelling stage:

- directlly affects efficiency and quality of the mathematical solution
- guarantees the adequation to the real life problem

PHARE Demonstration: Arrivals Management

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1. SUMMARY

This paper reports first results obtained from the real-time simulations in the frame of the second PHARE Demonstration (PD/2) performed during December 1996 to February 1997 at DLR in Braunschweig. The experimental set-up of three different configurations for the management of arrivals in an extended TMA airspace using the Tools developed within the PHARE programme in connection with DLRs Air Traffic Management and Operations Simulator (ATMOS) is described. A conventional arrival management system is compared with advanced arrival management based on time accurate trajectory predictions provided from ground as well as from the air. An overview on the advanced Ground Human Machine Interface developed for these experiments is given. Eight controller teams from seven European countries take part on the experiment. The first analysis of the collected data in terms of performance, workload and acceptance supports to follow the ideas of the presented operational concepts for the Approach problem further to be included within future Air Traffic Management Systems.

2. INTRODUCTION

The management of arrival streams into airports is a crucial part of each Air Traffic Management System. During arrival an aircraft descents from cruise level to runway altitude. Undelayed typical arrival flight times are in the order of 20 to 30 minutes. Compared to the other phases of flight like taxiing, departure, and en-route during arrival the aircraft has only little fuel left, finds most likely other aircraft in its neighbourhood influencing its own flight planning and execution and there are only small space and time buffers left to compensate deviations from a scheduled arrival time. Bottlenecks in the management of the arrival traffic have strong impacts on all other parts of an ATM/ATC system like the departure system and the en-route parts by either blocking the runway system for departures due to delayed landings or back-up in the feeding en-route sectors if the capacities of the approach sectors are reached .

Each approach system itself can be seen as a set of many subsystems each of them belonging to different boundary conditions like RWY direction in use , airport/aircraft equipment in use, visibility and so on. The transitions between the different subsystems have to be defined very precise and in advance in order to allow all participating actors - pilots and controllers- with their supporting tools to adapt for a change. Unpredictable cases like missed approaches or blocking of a runway have to be considered too. At the same time airline preferred profiles and environmental restrictions like noise abatement procedures have to be respected. In addition each approach area has to be treated for its individual characteristics depending of runway configurations, obstacles flight restriction areas and so on.

It is clear that in such complicated system it is not easy to find new solutions accepted by all parties involved like airliners, airports, ATC and citizens around an airport. New solutions aim to provide more efficiency and performance maintaining or improving the safety for all configurations.

It is also obvious that major changes have to be agreed on a world-wide level in intensive negotiations and discussions. It is the task of research to support these discussions by investigating the impact of new arrival management concepts and tools with respect to safety, performance, workload and acceptance .

The present paper describes an example of such investigation performed in the frame of the Programme for Harmonised Air Traffic Management Research in Eurocontrol (PHARE) . Most information of the next two chapters were taken from [1]. A good access to the PHARE programm contents and reference papers can be found on the World Wide Web [2].

3. PHARE PROGRAMME

The PHARE programme founded in 1989 has the objective to organise, co-ordinate and conduct studies and experiments aimed at providing and demonstrating the feasibility and merits of a future air-ground integrated air traffic management system in all phases of flight. The results of the programme should help to refine the description of the future Air Traffic System concepts needed to satisfy demand and provide information on the best transition from the current to the new system.

In PHARE a number of European research establishments assisted by the authorities concerned combined their ATC and aeronautics experience and resources. The participants in PHARE are:

- CAA/NATS (with sub-contracts to DRA Bedford & DRA Malvern), United Kingdom
- STNA and CENA, France
- DFS and DLR, Germany
- RLD/LVB and NLR, Netherlands
- EUROCONTROL Agency Headquarters Brussels and EUROCONTROL Experimental Centre, France.

The Commision of the European Communities participates in and supports PHARE. The FAA and Transport Canada are co-operating within the frame of relevant agreements.

The PHARE activities cover definition studies on future system aspects, experiments and real-time simulations ('Demonstrations') which are the final objective of the programme as well as tools and function development to support the Demonstrations.

4. PHARE DEMONSTRATIONS

The Demonstration work comprises preparation of the ground and air sites and the integration of the advanced tools and the Ground / Airborne Human Machine Interfaces. The first two Demonstrations PD/1 and PD/2 investigate ATM in the years 2000-2005 timeframe, whereas a third Demonstration PD/3 will be concerned with issues of the timeframe 2005-2015.

4.1 PHARE Demonstration 1 (PD/1)

The trials of PD/1 were carried out in 1995. PD/1 was concentrated on the en-route issue by simulating several en-route sectors and entry/exit conditions at TMA sectors. PD/1 was hosted by DRA at Malvern. A complete

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

description and the results can be found in the final report of PD/1 [3].

4.2 PHARE Demonstration 2 (PD/2)

PD/2 addresses the terminal approach issues by simulating several sectors of an extended TMA and emulating entry and exit conditions at en-route sectors. The trials were performed at the end of 1996 and during January/February 1997. In June trials including a real aircraft DLRs Advanced Technology Testing Aircraft Simulator ATTAS will be completed. The final report of PD/2 will be available July 1997.The present paper concentrates on this demonstration.

4.3 PHARE Demonstration 3

PD/3 will embark on multi -sector, multi - centre en-route and extended TMA planning issues. PD/3 will be hosted by CENA, NLR and EEC assisted by CAA/NATS and DLR. PD/3 will demonstrate air/ground integrated concepts for multi-sector planning, human centred approach and en-route /TMA interfacing.

5. EXTENDED TMA AIRSPACE IN PD/2

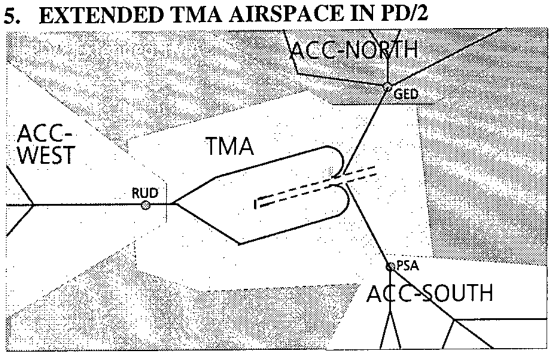

Fig. 1 Extended TMA in PD/2

Figure 1 shows in a schematic way the airspace used in PD/2 to model an Extended TMA for arrival traffic.

The organisation of the airspace is still assumed to be the same like it is today. The basic layout was taken from Frankfurt TMA. The core TMA is build up by one sector of about 30 NM diameter extended to the metering fixes Rudesheim RUD, Gedern GED and Spessart PSA. It reaches up to FL100 and CAS is limited to 250 kts in this altitude regime. The TMA is surrounded by three adjacent en-route sectors controlled by one area control centre i.e:ACC-West, ACC-North, ACC-South ranging up to about 100 NM from the airport (about 20-30 minutes flight time). This relates to the fact that the human functions 'planning' and 'tactical' control' are assumed to be still sector based in PD/2. The runway system with two parallel runways in use (25L and 25R) for arrivals in runway direction 25 is located in the centre of the picture. In contrast to the real Frankfurt system the parallel runways are assumed to be wake vortex independent. That is to allow an increase of the arrival traffic demand in the experiments to a full runway capacity of 66 arrivals per hour [4]. A runway 18 is assumed only for departure traffic. The dotted lines pointing to each of the parallel runways indicate the extended centrelines of an ILS for each runway with azimuth angle of 3 degree. At about the so called Approach Gate (in the following text referred short as Gate), a position 10 NM from threshold at 3000 ft, aircraft are asked to contact the Tower Controller on R/T when successfully established on ILS.

The simple arrival route structure used in PD/2 is shown as solid lines in the figure. Traffic from the north has to land on the north runway traffic from the south on the southern runway. Arrivals from the west can be guided either on a southbound or northbound route to the northern or southern runway. Basic RNAV capability is assumed to be the minimum airborne equipment. The departure route structure is assumed to be decoupled from the arrival routes in PD/2 and is not shown here. The departure problem will be tackled in PD/3. Some overflights were simulated in PD/2 crossing the TMA sector above FL 100 from different directions.

6. PHARE TOOLS IN PD2

Within separate PHARE projects tools and functions were developed and delivered to the demonstration hosting site at DLR Braunschweig (Germany) for PD/2. These prototypes were integrated into the real time Air Traffic Management and Operations Simulator ATMOS of DLRs Institute of Flight Guidance. The following PHARE developments were used in the PD/2 trials:

- The *Validation Tools (VAL)*

to support comparison of results of the various evaluation exercises.

- *Experimental Flight Management System (EFMS)*

to made available an EFMS that supports 4D flight management, air-ground digital data communication and handling of ATC constraints.

- *Airborne Human Machine Interface (AHMI)*

to provide an EFMS Interface for pilots.

- *Ground Human Machine Interface (GHMI)*

Within this PHARE project the guidelines for and the design and prototyping of the human-machine interface to improve the combined use of the ground tools together with a HMI training device were generated for PD/2. The concrete GHMI software development and integration was done by the PD/2 integration team at DLR hosting site in parallel to the integration and testing of the other tools.

- *Common Modular Simulator Environment (CMS)*

Here the standard interfaces for the connection of the new tools with the basic ATC functionality based on a modular client-server approach. were defined. The PARADISE Platform used to integrate the PHARE Advanced tools in PD/2 were delivered by this project.

- *PHARE Advanced Tools (PATs)*

PHARE Advanced Tools , providing the ground based support tools and functions for increased controller productivity.

In PD/2 the following subset of PATs were integrated:

6.1 Trajectory Predictor (TP)

For the ground system the TP provides the trajectory as new basic information entity extending the flightplan information in use today (for the airborne part an EFMS equipped aircraft can provide the information).

A trajectory in PHARE is defined as the description of the predicted progress of a flight in space and time (4D).

The description is given by a set of lateral points and a series of segments between them that builds a *route* in combination with a set of points describing the predicted height and time of an aircraft along its route: The *profile.*

The requirement for spacing of the calculated profile points is such that linear interpolation to be used between the points allow to predict altitude and time at any route position with sufficient accuracy.

The TP generates the trajectory information for each aircraft from take-off to landing. In PD/2 only the arrival part of the trajectory about 30 minutes flying time including the Top of Descent from cruise level until the approach gate (10 NM from threshold) was used.

The TP uses a database of aircraft performance characteristics, the initial flight plan and constraints given by the ATC environment under consideration (e.g. sector height constraints, standard arrival routes, sector transfer points) or constraints calculated by tools (e.g. a time constraint for the Approach Gate given by the Arrival Manager tool). Constraints are defined as windows in space and time through which the trajectory must be planned. The TP generates on request close-to-optimal 4D-trajectories for each aircraft. In addition the tool is able to calculate the earliest possible time and the latest possible time for a given point for which a trajectory can be calculated within given performance limits and constraints.

6.2 Conflict Probe (CP)

The Conflict Probe compares a new trajectory with each trajectories already stored within the flight database of the ground system. Any violation of separation criteria like radar separation, wake vortex separation or flight phase is located in space and time.

6.3 Flight Path Monitor (FPM)

The Flight Path Monitor compares each position report of an aircraft against the 4D position taken from the active trajectory stored in the ground system. Deviations in terms of distance in space and time are produced with the surveillance update rate for further processing by the GHMI to be displayed to the controllers or for management tools like the Arrival Manager. In addition a subscription is available to report if pre-specified deviation limits in space and/or time are reached.

6.4 Negotiation Manager (NM)

In PD/2 the Negotiation Manager takes care of the air/ground exchange of information with respect to trajectories. The tool controls the interface between the ground based tool set and the air/ground datalink system that connects with EFMS like equipped aircraft. In PD/2 the exchange of air/ground information via datalink is triggered by the Arrival Manager tool automatically. The air-ground communication in PD/2 consists of down-link messages containing airborne trajectories and up-link ATC constraints and clearance messages. The goal of this information exchange is to negotiate a contract to implement an airborne trajectory between air and ground system whenever possible.

6.5 Arrival Manager(AM)

The Arrival Manager forms the central tool in the PD/2 environment. The tool works over multiple sectors of an extended TMA in order to provide optimised scheduling and sequencing advisories for all arriving aircraft (Arrival Managers with this basic functionality are in use in today systems already based on arrival time predictors typically closely integrated within those tools using flight plan information e.g.: COMPAS [5]). In the advanced concepts used in PD/2 this basic functionality of the arrival manager was extended to be based on trajectory information either generated by air systems within an EFMS like equipment or ground based by a TP tool.

In addition route, profile, speed and arrival time advisories are generated based on the information of the trajectory and are transferred to the GHMI. The AM also provides the functionality to update constraints either by deviation events given by the FPM or by controller inputs that affect the contracted trajectory status. The functionality to revise the schedule and sequence in case of deviations or in case of controller inputs is also available for the Arrival Manager but was not exercised within the PD/2 measured trials.

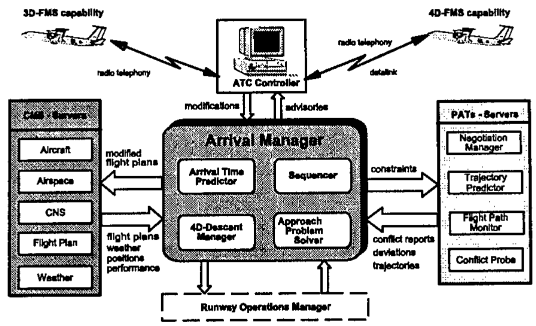

Fig. 2: Arrival Manager in the PD/2 context

Figure 2 shows the Arrival Manager embedded in the tool set of the PD/2 system. The box on the bottom showing a connection to a runway operations management system is not taken into account within the present PHARE programme. It is shown here to point out that arrival management functionality has to take into account runway conditions at the airport and that a predictable arrival traffic as supported by tools depicted here opens the option to close the gap between Arrival and Departure tools by systems supporting runway operations on airports. It is the task of future research activities to investigate how this gap can be closed in order to transfer the benefit of improved predictability of arrival traffic provided by the tools to the runway system on the ground.

The arrival manager is composed of four main components. Arrival Time Predictor, Sequencer ,4D-Descent Manager and Approach Problem Solver.

6.5.1 *Arrival Time Predictor*

The arrival time predictor gathers all necessary information, which are mainly airspace and flight plan data, to prepare a constraint list. This constraint list is sent to the TP tool for calculation of a preferred ground based trajectory together with the earliest and latest possible arrival times for the Approach Gate. If alternate routes are possible like the West Approaches in PD/2 a trajectory with the set of estimated arrival times also for the alternative routes is stored in a separate context. Each entry of a new inbound flight indicated by the ground system - normally at the boundary of the Extended TMA - activates the Arrival Time Predictor Modul.

6.5.2 *Sequencer*

The sequencer tool provides the sequencing and scheduling functionality of the Arrival Manager based on the trajectory information of all known aircraft. In the first step the preferred times at the Approach Gate are checked against separation violations in time. If no violation is seen the CP tool is triggered to check whether a separation violation between the trajectory under test and all other trajectories already planned by the system exists. If the CP reports no conflict the aircraft is scheduled for the preferred time. It is now known that a conflict free solution exists for this aircraft. If the aircraft is 4D-FMS equipped then the NM tool is activated to initiate a negotiation via datalink. The ground constraints list is uplinked and the aircraft sends down an airborne trajectory. This trajectory is checked again by the CP against all other trajectories already planned. If no problems are detected the airborne trajectory replaces the one calculated by the TP. If different aircraft are in conflict with their arrival times a branch and bound algorithm is activated to sequence according to predetermined rules like first come first serve, close gaps in the sequence, optimise wake vortex categories. The arrival times are varied within the earliest and latest times limits in

order to optimise the sequence. If alternative routes are allowed which even may belong to a different runway these routes will be checked for a better solution. This leads to a set of new constraints and the generation of a new trajectory by the TP fulfilling the new constraint for arrival times and possibly for a new runway allocation. If no conflicts are found by the CP tool the aircraft are scheduled for that target time. 4D-FMS equipped aircraft get in that case a constraint list uplinked which already contains the ground based optimised arrival time and route. If the downlinked trajectory fulfils the constraints and is conflict free the airborne trajectory also replaces the ground calculated one. The result of the planning is copied into the system plan by activation of the trajectory solution found. The GHMI also gets the information on the trajectory of new scheduled and sequenced aircraft, as well as the NM in order to initiate a clearance datalink message for an equipped aircraft to fly the previous downlinked trajectory.

At the border of the Extended TMA an equipped aircraft will go to the following sequence of air-ground negotiation steps in order to get a contract to implement the trajectory automatically:

1. *Uplink of constraints*

Uplink message containing for arrivals at least the route identifier and time constraints at the gate.

This requires that the AM Manager has completed the 4D-planning of this aircraft on the basis of informations on the ground. This can be a ground based trajectory calculated by the TP or a trajectory information already downlinked in a previous sector.

2. *Downlink of Trajectory*

If the aircraft has accepted the uplinked constraints it downlinks a trajectory which fulfils the constraints based on the newest weather information obtained. If the aircraft cannot fulfil the constraints it sends down a message unable to fulfil the constraints. This aircraft will then be guided via Radio Telephony (R/T) as an unequipped aircraft.

Every downlink of trajectory causes a new check of this trajectory in terms of conflicts and constraints against all other active system plans on the ground.

3. *Uplink Clearance*

If as normally expected there is no conflict, a „contract given" message is exchanged.

6.5.3 *Approach Problem Solver*

In case of problems like conflicts found by the CP the AM varies altitude and time constraints on other route points before the approach gate in order to obtain a conflict free trajectory.

This capability included in the PD/2 Arrival Manager is only very limited because within the PATs a separate Problem Solver tool which takes into account all trajectories, not only the arrivals as the AM does, was foreseen for this task. If no conflict free trajectory solution could be found the scheduled time in the arrival sequence is maintained but the trajectory is marked 'in conflict' visible for the controllers. Then the arrival manager provides an arrival slot for those aircraft but does not provide a conflict-free solution for that slot. It is now the task of the controllers to find a solution not known by the supporting tools. This is normally easy to achieve simply by deviation from the route to avoid the predicted conflict area. One can see on this example that restricting the tools to work for a fixed route structure only like in PD/2 makes the problem solving task more difficult and/or leads often to not very efficient solutions. On the other hand although non-route restricted tools will probably find easier and more optimal solutions they may be not as predictable by the human controllers in the loop as in case of a fixed route based tool reflecting the standing agreements used by the humans in the control loop.

6.5.4 *4D-Descent Manager*

The task of the 4D-Descent Manager module is to support the implementation of each scheduled trajectory. This is done by translating the trajectory representation into advisories applicable as control commands via R/T. Those advisories are generated for turns, descents to FL, descent rates and speeds. In addition the position and time where and when the specific advisory should be applied is produced. These data are transferred to the GHMI before expected execution time in order to allow the advanced indication to the controllers. Deviation messages as given regulary by the flight path monitor are used by the 4D-Descent Manager to decide if the guidance mode of an aircraft has to be changed.

7. ROLES OF CONTROLLERS

In PD/2 the split of tasks between Tactical Controllers (TC) and Planning Controllers (PC) was maintained using the Frankfurt structure of today as a basis. In general the order of priorities for the work of all controllers is:

1. safety;
2. efficiency of the overall traffic (optimal use of airspace capacity available in terms of delay reduction, minimal fuel consumption and noise abatement);
3. efficiency for flights on the basis of individual aircraft performance and airborne requests.

The role of the Planning Controllers is one of co-ordination, both intersector and intrasector co-ordination. The control and supervision of the air-ground datalink if available is given to the PCs. The role of the Tactical Controllers (TC) is to ensure conflict-free passage of the aircraft through their airspace. All direct radio telephony with the aircraft is performed by TCs. The transfer of control to and from neighbouring sectors is coincident with transfer of communication. To ensure a conflict-free situation also during the handover phase between two sectors it is a standing agreement that each aircraft will enter an sector over Entry Fixes (EF) and also will leave an sector over defined fixes. For the arrival traffic these are the Metering Fixes (MF) at the border of the TMA. Modifications of these agreements can be co-ordinated between the TCs on an ad hoc basis if necessary. These agreements are:

- to handover aircraft only laterally spaced,
- to apply vertical spacing to groups of aircraft (so-called 'packets'),
- to apply heading commands to aircraft before handover in order to achieve lateral de-conflicting, if only vertical spacing is used at the handover fix,
- to fill and to empty holding stacks,
- to transfer aircraft in distinct flight levels.

The concept of PD/2 distinguish between three guidance modes as depicted in fig. 3:

- An aircraft in Class A guidance mode is 4D-FMS and datalink equipped and has the clearance to implement its own trajectory automatically.
- A Class B guidance mode is available for all aircraft that are guided via R/T and for which the ground system has support in form of a conflict-free trajectory and the associated advisories.

- A Class M or manual guidance mode where the aircraft is guided via R/T without valid trajectory for it as applied in the today's systems.

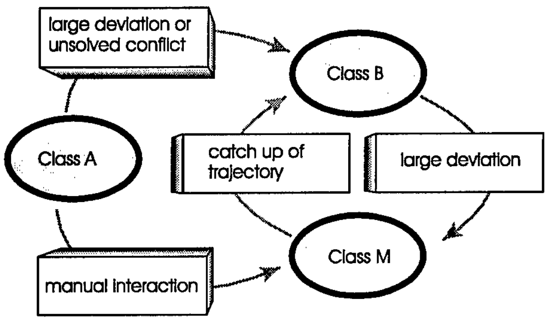

Fig. 3: Transition of Guidance modes in PD/2

In close co-operation with PC a TC monitors the flight progress of a Class A aircraft.

If no problem is detected by TC these aircraft will fly with no other R/T communications than initial call when entering and frequency change when leaving the sector.

Every time TC sees the necessity due to safety reasons, TC can guide the aircraft via R/T.

The first heading, speed and level change command given via R/T to a Class A aircraft implies that this aircraft is guided via R/T further. A negotiated contract between air and ground via datalink is no longer valid then.

The status of aircraft automatically changes from Class A to manual mode as the system is updated about such tactical intervention by a GHMI input.

If such event happens during an uncompleted negotiation process via datalink this aircraft is treated further as an unequipped aircraft, even if the negotiation cycle via datalink will be completed successfully afterwards.

As a general rule R/T communication always overrules datalink communication.

If an Arrival Manager gives automation support for the 4D-Guidance of aircraft along the planned route, the TC transmits the 4D-Guidance advisories produced automatically by the ground system via R/T to the aircraft (Class B guidance).

Please note that it is not difficult to extend the definition of Class A aircraft for aircraft that have no datalink but 4D-FMS equipment if the negotiation process to implement a trajectory is performed via R/T. The same is true for aircraft only RNAV but datalink equipped. Here the R/T communication to implement the ground based trajectory could be reduced by using the datalink to transfer the control messages. The principle three states of guidance modes will be the same: Airborne trajectory implementation, Ground based trajectory implementation and guidance based on tactical control only.

An aircraft once degraded to Class B or Class M mode never will get back to Class A whereas a transition between Class M and Class B guidance is always possible depending on the distance of an aircraft from its 4D-position on the planned trajectory sensed by the FPM.

The option to allow a re-negotiation process via datalink in case a 4D-equipped aircraft is closing up to its planned trajectory has to be considered also. Within dense traffic TMA such re-negotiation process have to be performed rather fast. The update rates should be close to the surveillance component update rate (usual about 4 seconds in a TMA). This option was not studied in PD/2 because the available tool prototypes were not fast enough at that time.

7.1 En-route controllers

In PD/2 only the Area Control Sector West (ACC-W) was staffed with one Tactical Controller (TC-W) . The other ACC sectors North and South were simulated automatically as if an ideal controller team was working there. The role of the Tactical Controller ACC Arrival West TC-W controls the arrival traffic and overflights (traffic from and to other airports) within the West Sector.

Moreover in PD/2 the TC-W also performed the task of the Planning Controller West (PC-W) because only the co-ordination with the adjacent TMA sector was modelled.

7.2 Approach controllers

The TMA sector is controlled by Approach (APP) controllers

Two working positions for tactical controllers, a TC-P (for Tactical Controller APP Pickup) and a TC-F (for Tactical Controller APP Feeder) are needed, which work within the same airspace but on different R/T frequencies.

This team of the two tactical controllers is completed by a Planning Controller Approach (PC-A).

The three APP controllers are sitting side by side and share their displays, supporting the necessary close teamwork and co-ordination between them in a very flexible and natural way.

7.2.1 *Planning Controller Approach (PC-A)*

The Planning Controller Approach has the following tasks:

- Identify and assess potential conflicts between aircraft offered into the sector by use of flight-plan/trajectory information, AM data, FPM and CP messages and Radar data to.
- Notify TC-P and TC-F on any special conditions about the traffic before entering the sector.
- Co-ordinate with TC-P and TC-F if a Class A to Class B aircraft planned change has to be applied.
- Co-ordinate with PC/TC of adjacent sectors if entry and exit conditions have to be changed.

7.2.2 *Tactical Controller Pickup (TC-P)*

The main tasks of TC-P is to establish the AM landing sequence and to prepare a safe and efficient runway allocation for the TC-F.

In close co-operation with TC-F the TC-P will be responsible for ensuring conflict-free passage of aircraft (minimum separation: vertical 1000 ft; lateral 3 NM, for Wake Vortex relevant combinations of aircraft up to 6 NM) through the TMA airspace. The tasks of TC-P can be summarized:

- Perform R/T Communication with aircraft (At least initial contact confirmation and frequency change command to initiate handover to TC-F for arrivals and to other ACC TCs for overflights),
- check if aircraft have got the latest weather information,
- surveillance of aircraft using the radar information,
- application of guidance and control commands in order to avoid separation conflicts,
- apply guidance commands until the transfer region (vicinity of extended centreline for arrivals where the transfer to TC-F takes place, Exit Fix for Overflights) in order to fulfil AM schedule and sequence using the AM display and 4D-advisories for Class B arrival aircraft,
- update the ground System with the guidance commands given,
- negotiate with TC-F and TCs (*and/or PCs*) of adjacent sectors if standing agreements have to be changed,

- if necessary hold aircraft within the sector either on request of TC-F or in case of any doubt on the status of standing agreements.

7.2.3 *Tactical Controller Feeder (TC-F)*

The task of TC-F is to guide the aircraft conflict-free (minimum separation: vertical 1000 ft; lateral 3 NM, for wake vortex relevant combinations of aircraft up to 6 NM) to the extended centreline, to give ILS clearance and to establish separation over the threshold by speed commands up to the Outer Marker (4 NM from threshold).

Normally near the gate (10 NM from threshold) the transfer of communication to the Tower Controller takes place.

The tasks of TC-F can be summarised as follows:

- Perform R/T Communication with aircraft (At least initial contact confirmation, ILS clearance and frequency change command to initiate handover to tower controller for arrivals),
- surveillance of aircraft using the radar display and weather display,
- apply guidance and control commands in order to avoid separation conflicts,
- guide the aircraft to the approach gate in order to fulfil AM schedule and sequence using the AM display and 4D-advisories for Class B arrival aircraft,
- Update the ground system if an aircraft has to be guided manually, if the AM guidance support can not be applied,
- give clearance for allocated ILS,
- establish separation on ILS,
- inform PC-A and TC-P if the sequence cannot be met,
- negotiate with TC-P and Tower Controller if standing agreements have to be changed,
- update the electronic system if changes in aircraft status and applied commands are not in agreement with the recommended advisories from the 4D-Guidance support system.

8. ARRIVAL CONCEPTS IN PD/2

The real-time simulations of PD/2 compare three different modes of operation characterised by three organisations ORG0, ORG1 and ORG2:

ORG 0:

A reference mode, in which the controller has to handle the traffic samples with the standard means of today (radar data, flight plan data, paper flight strips, weather information, radio communication) and assistance by an arrival planning system with basic sequencing and scheduling functionality.

ORG 1:

An advanced mode with 4D profile planning detection and resolution of planning conflicts.

An arrival planning system (Arrival Manager Version 1) avoids planning conflicts by separating all arriving aircraft in space and time.

The Arrival Manager is assisted by the following PATs: Trajectory Predictor, Conflict Probe and Flight Path Monitor.

The implementation of ground calculated 4D - trajectories is performed by using conventional radio communication.

Advisories displayed to the controller are generated by the ground system in order to support the controllers to meet time constraints of the Arrival Manager.

Deviations of aircraft from the planned trajectory as well as unsolved conflicts between planned trajectories (detected by the Conflict Probe) have to be resolved manually by the controller.

The system supports the controller in this process by measurement (done by the Flight Path Monitor) and display of deviations in time and space against the planned trajectory (calculated by the Trajectory Predictor).

Flightstrips (paper) will no longer be used.

The controller works within a stripless environment (even no electronic strips).

The interaction between controller and the ground system but also between the controllers will be supported by label interaction mechanism within the displays.

ORG 2:

A more advanced mode, additionally to ORG 1 with the introduction of an air-ground integrated system.

Here 4D - FMS equipped aircraft use datalink to negotiate and implement airborne calculated trajectories that fulfil the constraints developed by the AM in order to implement an arrival sequence schedule (CLASS A aircraft guidance).

For unequipped aircraft the trajectory support will be given by the ground system as in ORG 1 (CLASS B aircraft guidance).

As in ORG the AM is assisted by Trajectory Predictor, Conflict Probe and Flight Path Monitor.

In addition the management of the air - ground communications will be performed by a Negotiation Manager in close co-operation with the Arrival Manager.

The comparison of ORG 0 against ORG 1 allows to measure the effect of transition from a flight-plan on paper driven system to a paperless ground trajectory based arrival management. The comparision of ORG 1 vs. ORG 2 allows to measure the effect of introduction of automatic airborne guidance within an Extended TMA for an air-ground integrated arrival management.

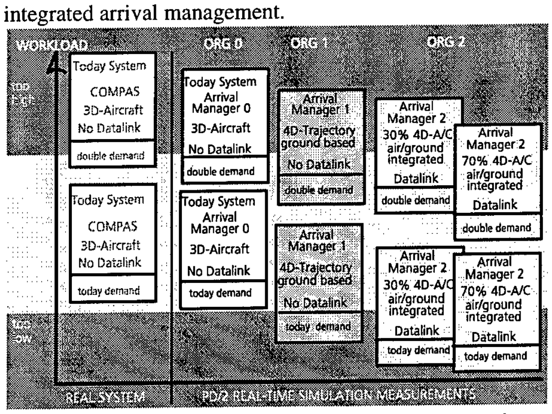

Fig. 4 Estimated workloads for PD/2 Organisations

Figure 4 shows the different Organisations on a arbitrary workload scale used for the layout of the experiment.

The two boxes on the left describe the situation in a today system. If traffic demand for arrivals would be doubled from a today level of about 35 to 70 aircraft per hour the workload of the approach controllers will certainly too

high. The other boxes show the effects expected in real-time simulations. The measured workload for ORG 0 may be lower compared to the reality because not all effects are modelled in real-time simulations and the stress of the controller is lower knowing to be in a simulated world. The transfer of the results of real-time simulations to a real situation is therefore not allowed. But the relative comparison of the ORGs within the simulated world can give at least a qualitative indication wether the new concepts have the potential for improvements or not.
Besides the traffic demand the share of Class A aircraft was varied during the experiments to reflect the different degrees of automation possible in a ORG 2 system.

9. EXPERIMENTAL ENVIRONMENT ATMOS

The Air Traffic Management and Operations Simulator ATMOS was used to host the PD/2 simulations. ATMOS is part of a large real time simulation suite operated by DLRs Institute of Flight Guidance at Braunschweig.

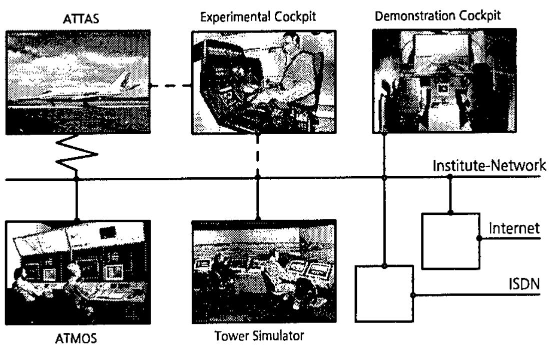

Fig. 5: DLR ATM Simulation Suite

Fig. 5 shows the facilities available. They are connected by a local area network (LAN) based on Ethernet. During PD/2 the Advanced Technology Testing Aircraft System (ATTAS) real aircraft and the Experimental Cockpit equipped with an EFMS were connected with ATMOS.
The ATMOS kernel consist of one DEC VAX 3200 workstation running under VMS operation system (OS). Here the multi-aircraft model in connection with 6 terminals for the pseudopilots is installed. The LAN connects this workstation with 6 Pentium PCs under Linux OS and X-Windows. Three of them are driving a large SONY 2k*2k resolution Display for the radar display on the controllers working positions. The other support 19'' Displays at 1k*1k resolution for the Arrival Management Display mainly on each working position. Three controller working positions have been installed and equipped with radar screens for Tactical controllers (TC -W, TC-P, TC-F) and several displays for different information and planning tools at the planner positions (PC-A).
One additional PC under Linux is used as a central data and supervisor server for GHMI. The PATs integrated into a CMS platform runs distributed on three SUN SPARC 20 workstations under Solaris OS. One Silicon Graphics workstation under Irix OS runs a datalink simulation that is connected to an additional SUN workstation interfaced to the EFMS and the terminal computer of the Experimental Cockpit in which the EFMS and AHMI is integrated.
The Experimental Cockpit can be operated either on the ground together with a flight simulation or can be installed in the rear ATTAS. ATTAS is one of DLRs testing aircraft a VFW 614 reconfigured as an in-flight simulator. A data connection with ATTAS in flight is given by a high capacity telemetry datalink. An additional Silicon Graphics Workstation under Irix OS was used to store and to pre-process the data collected during each run. 6 Video Cameras with three Super VHS video recorders were used to document each run on tapes. The audio channels on the video tape were used to store the communication from each of the three radar working position. A specially designed Intercomm simulates the R/T on the three frequencies (for TC-W, TC-P and TC-F) between controllers, pseudopilots and the pilot of the experimental cockpit via headset or microphone and loudspeaker installed at the controllers and (pseudo)pilots working positions. In addition to the audio signal the time when a controller presses its microphone button is provided by the Intercom. For ORG 0 simulations an extra paper strip holding device could be mounted on the table in front of the displays of each controller working position. For the advanced organisations a mouse-pad with three-button mouse was the only device. For each controller a special designed three key input/three character display device was connected with ATMOS placed on the table in front of each controller to store the controller inputs for the Subjective Workload Assessment Technique (SWAT) applied in PD/2 [6]. During a run each controller was informed by blinking of the displays on the device to give its subjective workload assessment in terms of time, effort and stress. After each run the subjective workload assessment for NASA's Task Load Index Method (TLX) [6] could be done by mouse in extra pop-up windows on each controllers position.
In addition to the main simulation hardware the core elements were doubled to allow a second simulation for parallel training of a new controller team. For this training system located in an extra training room BARCO multi-sync screens were used for the radar displays instead of the large Sony screens and the PATs/CMS platform runs on one SPARC 20 only. This training system was operated without datalink simulation, without pseudopilots and without R/T and workload assessment tools. The controller had to use the label interaction mechanism by mouse developed for the advanced ORG 1 and ORG 2 system also for the training of the ORG 0 system. An extra GHMI training software was installed on each of the GHMI display PCs. By this software the controllers got an briefing and training of the GHMI elements on the first day of one week training. The remaining time the controller were trained in the different ORGs as a team by using traffic samples of increasing traffic demand using the real time simulation and the tools as in the main simulator.
Fig . 6 shows the configuration of ATMOS as used in PD/2.

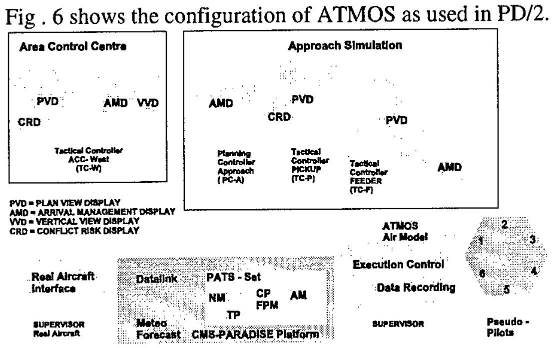

Fig. 6 ATMOS configuration in PD/2

10. GHMI

The GHMI used in PD/2 for the advanced Organisations provides a prototype of a paperless system for approach control. It was designed within the PHARE project GHMI.

The coding and optimisation with respect to the real-time requirements was done during the test phases of the PD/2 system by the local PD/2 team with the support of Frankfurt Approach expert controllers. The coding was done in X-windows using TCL/TK and C++ . It runs under Linux but also under Solaris and Irix OS. It consists of a multi window environment that can be configured with the help of a GHMI administration tool to allocate the different tools (windows) to the different screens at the controller working position . For ORG 0 this system was used in a reduced mode together with paperstrips for flightplan information and as controllers scratchpad. The sequence of arrivals was indicated on a time ladder of the Arrival Management Display (AMD). The Plan View Display (PVD) simulates a conventional radar system with a two-line label at each target showing callsign, height and ground-speed. The different windows allocated to the controller positions for the advanced Organisations are listed in fig. 6. The main elements available on each working position were the Plan View Display for the Radar information together with a Conflict Risk Display (CRD) in case of conflicts between trajectories on the large screen and an Arrival Management Display for the planning controllers on the smaller screen. Only for the TC-W additonal Sector Inbound List windows were shown on the PVD in order to provide the flight plan information in advance for selectable entry and exit fixes (in PD/2 the West sector uses NTM and RUD). While the AMD occupies the whole 19'' screen in the approach control half of the screen were used by an additional Vertical View Display (VVD) window in the ACC-position. This window provides a view of the vertical traffic over RUD in order to allow to control and interact as with the plan radar display in a paperless environment over fixes where a holding is possible. This is necessary because the scale of the radar picture of the PVD is so large that a holding pattern cannot be resolved sufficiently (in a flight strip system this is done by sorting the paperstrips on the table in accordance to the occupied levels in the holding) in additon a label interaction via mouse as used in PD/2 is cumbersome in case of lot of targets at the same lateral point.

10.1 Plan View Display

The PVD shows the plan view of the airspace together with the labeled radar targets . A radar tool box window allows the controller to select the centre, the scale, the number of history points displayed together with the radar targets as well as the airspace elements to be shown and the label deconfliction method. In addition the controller can de-select the Conflict Risk Window (CRD) that pops up every time a conflict was detected between trajectories. This window indicates each conflict as small red box in a coordinate plot with an ordinate scale in distance of conflict in minutes and minimum distance at conflict time in NM at the abscissa scale. The callsigns of the aircraft belonging to that conflict are listed on the left at the time scale by clicking the red box with the mouse the controller could force the system to show also with red frames the labels of the associated aircraft at PVD and AMD. Please note that no short term conflict was included in the PD/2 system.

10.1.1 *Aircraft Label*

The main interaction mechanism for the advanced Organisations is provided by the labels associated with different targets. A controller selects a label simply by moving the mouse cursor over the label. Selection is indicated automatically by an background field containing the label lines in inverse colour. The label colours grey, pink and white indicate whether the aircraft is in control by other controllers or is in a transfer status or is under the control at the own working position. Transfer could be initiated by clicking a transfer field in the upper left corner of each label. A second slower method is available to input level, speed, and rate of descent/climb values by pop-up menus at the labels. By clicking on the heading field an arrow can be turned around the radar target by the mouse helping to select an heading value indicated in a number field. Inputs are done always with the left mouse button. By pressing the right mouse button over a label the label information is extended by additional data like destination airport, weight class etc. The same label interaction was also available in addition on AMD and VVD by moving the mouse over the callsign indicator of an aircraft .

The target shape shows the equipment of an aircraft. A square indicates 4D-equipment (data-link and 4D-FMS) a circle indicates non-4D equipped aircraft. A 4D aircraft with a cleared contract (Class A aircraft) is shown as filled square. Class B aircraft (with ground trajectory support only) are indicated as open circle or square. If an aircraft is assumed to be guided manual by the system the target becomes yellow. The advisories of the Arrival Manager are displayed in orange colour in a third label line for advised height, indicated airspeed , heading, rate of descent preceded by a tick marker field that can be clicked on by the controller if the R/T command was applied. In that case the third line only shows the last given cleared FL if the aircraft has not reached it. The orange advisories disappears automatically when the time of application is reached.

10.1.2 *Trajectory representation*

Figure 7 shows the PVD representation with selected label and complete trajectory on the example of SAS171 arriving via a northern route via metering fix Gedern to RWY 25R on the left bottom of the figure.

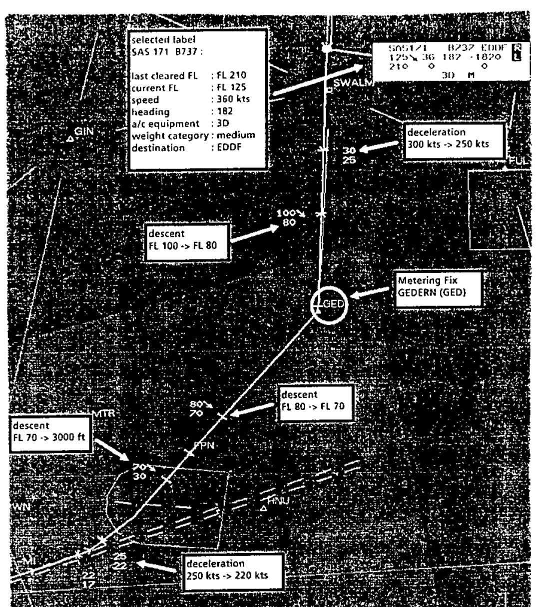

Fig. 7 Trajectory Presentation at PVD

The trajectory information is visible at the PVD graphically as blue lines along the whole route for each aircraft individually. The planned positions of an aircraft is marked

as a blue cross at the trajectory line. An other option is available to make only the future planned path for all aircraft visible as blue lines starting with a cross at the planned present position. The length of this 'futur-line' is selectable (in steps of 1 minute). Special markers on that trajectory lines indicate significant positions when the aircraft state will undergo changes like start/end of descent or speed changes together with the previous and new target values written at those markers in two lines. Independent of the blue trajectory representation. For CLASS B aircraft in additon yellow marker at the lateral position show where to apply the next advisories. An open square was used for a heading, a tilt cross for altitude and a cross for speed advisory positions. These markers disappear when the advisory was marked as given by a controller.

10.2 Arrival Management Display(AMD)

Sequence and scheduled time calculated by the AM is represented on a time scale (time ladder), progressing from top to bottom. Figure 8 shows the layout for the Approach Controllers. Here the time for the Approach Gate is the reference time (in ACC time over metering fix).

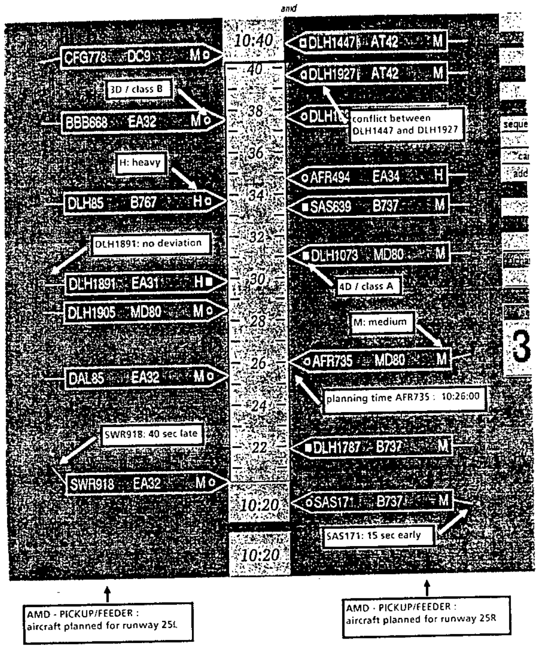

Fig. 8 Arrival Management Display Approach

The input buttoms shown at the right allow to inform the Arrival Manager about significant plan constraints changes like e.g. RWY direction change or necessity to insert a slot or change of the minimum separation in use. These buttons were not used in PD/2 in order to keep the whole traffic demand during the experiments unchanged by controller inputs.

Aircraft labels on the left (right) indicate a runway allocation 25L (25R). On ACC displays the left/right positions do not show the allocated runway but are used to avoid overlapping labels.

The aircraft labels are framed in different colours showing approach directions (blue = north, yellow = south , green = west).

At the end of each label frame the angle of a tail-line shows the deviation in time as measured by the FPM in a second scale. A tail pointing to the top (bottom) indicates 60 seconds delay (60 seconds early) whereas a horizontal tail line indicates 0 seconds delay.

Figure 8 shows some examples of early and late times compared to the scheduled time.

11. EXPERIMENTAL SETUP

11.1 Measurement Programme

The three Organisations were combined with two different arrival traffic demand levels of 49 and 69 aircraft per hour. These Organisations were investigated by real time simulation trials with ATMOS in December 1996 to February 1997. Each of eight controller teams (3 Approach and 1 ACC controller) from France, Germany, Great Britain, Italy, Netherlands, Rumania and Sweden, performed a measurement programme of one week after one week training on the training facility. Civil, military and mixed controllers teams operated the system.

Fig. 9: Working positions of ATMOS during the PD/2 Experiment. From back to the front the controller West ACC, Approach Planner, Pickup and Feeder. Experiment observers are placed in a second row.

Each team has to perform 8 measured runs as indicated in figure 4 (2 for ORG 0, 2 for ORG 1 and 4 for ORG 2 (30% and 70% Class A) and one demonstration run with EFMS equipped Experimental Cockpit in the loop of a ORG 2 scenario.

The traffic demands were constructed by using Frankfurt demands of today as a basis and adding additional traffic within the gaps for the high traffic scenarios. The traffic level reached its maximum about 20 minutes after simulation start and remains there until the end of a trial after 90 minutes. During the high traffic runs about 4 (2 in medium traffic) trajectories in conflicts has to be solved by the controller manually in order to demonstrate the behaviour of the advanced ORGs in transitions between the manual guidance / machine supported guidance modes.

12. MEASUREMENTS

The objective of the PD/2 measurements was to measure the effect of introducing the new tools and concepts in terms of performance, workload and acceptance by the controllers.

The methods to be used in the PHARE demonstrations were defined by the VAL project. A brief description and references can be found in [6].

In order to measure the differences between the ORGs in terms of system performance all relevant system outputs like aircraft positions, aircraft states, system-plans, operational data as event records of controllers and pseudopilot inputs were stored. To measure associated workload simulation events like times of label selection or button of microphone or mouse pressed were stored. Experimental observer noted significant event like pseudopilot errors and the comments of the controllers. This was accompanied by collection of operator judgements

collecting SWAT ratings during and Nasa-TLX ratings after each trial. The trials were documented in video and audio on tape in addition. To get the opinion of the controllers about the system questionnaires has to filled out after each run. Also debriefing sessions took place and were documented by audio tape to collect controller remarks and comments on the runs. The sequence of the ORGs and the order of high and medium traffic scenarios were varied between the different controller teams in order to reduce effects implied by a special order (learning effects of GHMI and tools).

PHARE Evaluation Criteria

performance (quantitative traffic handling) — workload — acceptance (operator approval)

PHARE PD/2 Data Collection

System Output	Operational Data	Operator Judgements
• Position (radar) data per aircraft	• Relevant simulation events	• Questionnaires
• Aircraft state data per aircraft	• Controller inputs (event records)	• Debriefing interviews
• Flight plan/way-point data per aircraft	• Pseudo-pilot inputs (event records)	• NASA-TLX
	• Video/audio documentation	• SWAT Ratings
		• SWAT Scales

Fig. 10: Evaluation criteria and collected data

When the trials of one ORG were completed a questionnaire about that organisation were filled out. The questionnaires consisted of questions regarding simulation, GHMI , operational concepts and tools used that could be answered in a 6 points rating scale from 'strongly disagree' up too 'strongly agree'.

13. FIRST RESULTS

At present the analysis process is ongoing, but first results are available already. It should be pointed out again that a direct comparison of the absolute values measured here with real traffic cannot be made, but comparative consideration of the values attained under the same simulation conditions is valid and furnishes relative conclusions. The analysis is done by comparing ORG 0 against ORG 1 to look on the effects of introducing the advanced GHMI and the PATs tool set and by comparison of ORG 1 versus ORG 2 to look on the effects of increasing portion of Class A aircraft (0%, 30% and 70%).

The data presented here show the results for the different ORGs for mean values achieved by the different controller teams. The error bars indicates $\pm$ 1 standard deviation. The Wilcoxon test was used to test wether ORG 0 vs.ORG 1 and the Friedman Two-Way Anova test was used to test wether ORG 1 vs. ORG 2(30%) vs. ORG 2(70%) results are statistically significant (level of significance 5%).

13.1 Traffic data and quality of service

A landing rate of 42 aircraft/hour were achieved in all ORGs for medium traffic scenarios. In high traffic the landing rate could be increased significantly from 62 in ORG 0 to 64 aircraft/hour in ORG 1 (also reached in the ORG 2 trials).

The mean flight time per a/c defined as the time from entry in the simulation until the time needed to reach the approach gate goes down significantly from about 25.2 to about 24.4 minutes. These lower values are reached for all ORGs in medium traffic. The variation between the different controller teams is also reduced as can be seen in figure 11.

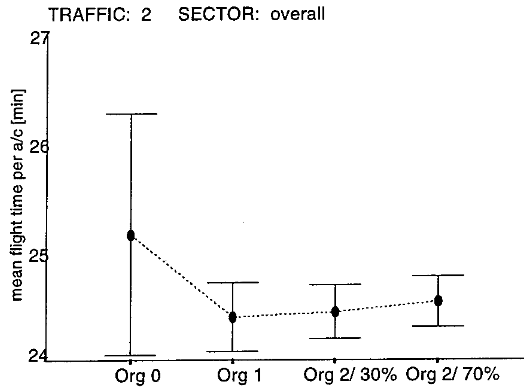

Fig. 11: Mean flight time per aircraft in high traffic

The mean inbound delay is defined as difference of preferred time at gate with the overflight time at gate (tool induced delay + controller induced delay). It goes down again to the same values as reached in medium traffic for all ORGs.

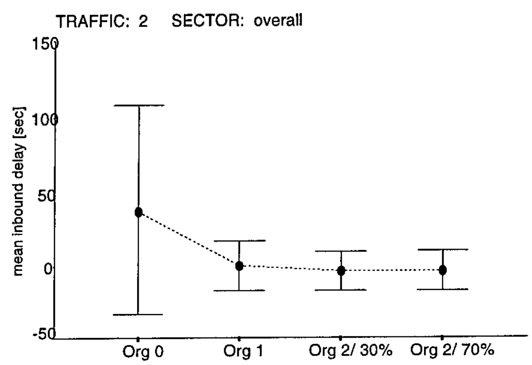

Fig. 12: Mean Inbound Delay per aircraft in high traffic

The precision at which the controller implements the proposal of the Arrival Manager is indicated in figure 13 by the root-mean-square(RMS) of the differences planned times with overflight times at gate.

The RMS precision of delivery at the gate goes down significantly from about 2 minutes to about 40 seconds in high traffic between ORG 0 and ORG 1/2. The same result is seen if only Class B aircraft are taken into account.

In general can be said that with introduction of the tools the variation in the work styles is reduced between the teams and therefore the predictability of the traffic is increased and can be maintained as for medium in higher traffic demands.

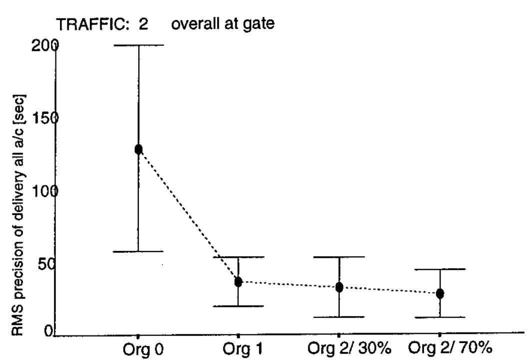

Fig. 13: RMS Precision of delivery of all non Class A aircraft in high traffic

13.2 Workload Data

Besides the subjective measures using SWAT and NASA TLX the number of instructions and the R/T load were analysed to get some objective workload indications.

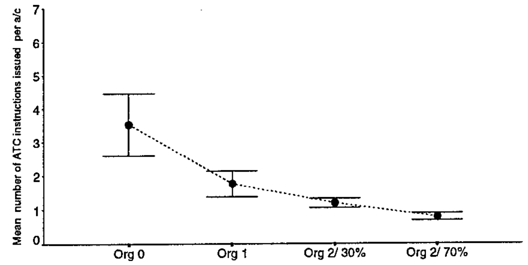

Fig. 14: Mean R/T instructions per a/c applied by Pickup in high traffic

The mean number of R/T intructions per hour for TC-F and TC-W showed no significant effects. Here the mean frequencies are about 130 instructions/hour for TC-W and 200 instructions/hour for TC-P. The pickup controllers R/T frequency goes down significantly from ORG 0 vs. ORG 1 from about 250 commands per hour to 200 per hour. These findings are supported also by counting the mean number of ATC instructions per aircraft seen as pseudo-pilot inputs in the system (fig. 14) with about 3.6 (ORG 0) down to 1.8 (ORG 1) commands per aircraft.

The sector controllers showed an increase of ATC instructions per aircraft from about 3 to 5 comparing ORG 0 with ORG 1. This seems to reflect the fact that the quality of the tools is still sub-optimal and/or does not fit with their usual working style. From observations during the trials and a closer look at the raw data it is apparent that in ORG 0 sector controllers tend to let aircraft fly without intervention, if possible, until close to metering fix RUD, that is just before entering the TMA. Only then they give descent and speed reduction commands. Whereas during debriefings controllers complained that a number of generated advisories in ORGs 1 and 2 are unnecessary or even unrealistic, e.g. multiple descent and speed advisories instead of one continuous descent or one speed reduction, thus causing more commands to be issued if all advisories are accepted.

Comparing ORG 1 vs. ORG 2 the frequency load is reduced with increasing Class A contributions for all controllers significantly. This is not a surprise when silent aircraft are introduced.

The percentage of simulation time used for R/T is significantly reduced for the pickup from about 22% to 18% , no significant effect is seen for the feeder (~20%).

Again a reduction is significant with increasing class A contribution for all controllers.

In medium traffic 10% to 15% is used for R/T . A reduction for the feeder is significant. TC-W time seems to increase (not significant) from ORG 0 to ORG 1. All controllers R/T show significant reduction with increasing Class A share.

TLX analysis failed to give significance in differences between ORG 0 and ORG 1.

The values for the TC-W sector show a tendency effect of increase of workload. These findings agree with the higher number of advisories issued in ORG 1 compared to ORG 0.

In high traffic the workload judgement of the planner for the approach team becomes less in ORG 1 compared to ORG 0.

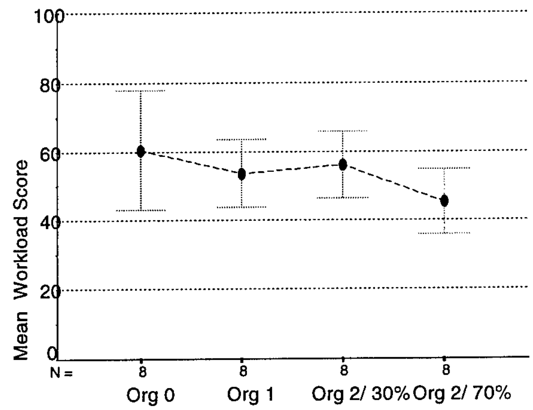

Fig. 15 TLX workload scale pickup controllers high traffic

SWAT workload measurements show a significant reduction effect between ORG 0 and ORG 1 in high traffic scenarios for pickup and planner (the planner was briefed to rate the workload for the TC pickup-feeder team because in ORG 1 and ORG 2 the workload for the planner itself appears too low because no changes in the planning was allowed in PD/2. For feeder and TC-W no significant difference could be seen. Medium traffic as well as Class A aircraft contribution do not give significant differences.

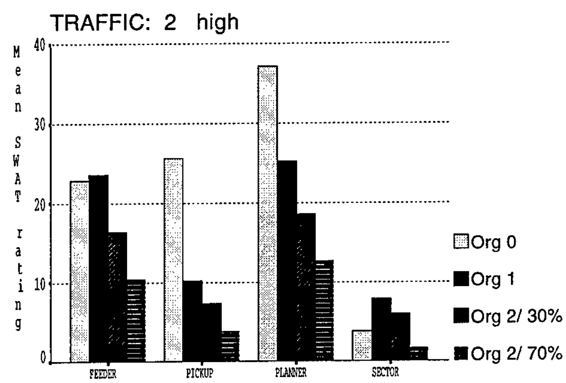

Fig. 16 SWAT workload scale

13.3 Acceptance

A first analysis of the questionnaires and debriefing sessions shows that traffic samples and way of feeding the sectors was well accepted. Controllers accepted simulation environment and training sufficiently well. The training level of the pseudo pilots were appreciated.The training period before the trials was rated significantly positive.

The GHMI mouse interaction was significantly accepted as suitable. The Plan View Display features were well accepted as well as the pop-up menus. Size of windows and colour coding were accepted as useful as well as the indication of aircraft mode of operation (class A, B or manual). Only in tendency the screen layout as well as readability of text information was accepted. The option to change the length of the depicted trajectories was significantly accepted.

The accessibility of aircraft to mouse clicks was detected as improvable. The reason for this is that busy working leads to imprecise mouse movements. Sometimes the selection area was already left before the mouse button was released (mouse release was taken as selection event).

That Class A guidance mode will reduce workload was significantly agreed. A significant proportion of controllers would prefer all aircraft Class A, but many controllers do not like the pure monitoring then ('feel boring', 'underloaded'). That points to a possibly problem of job satisfaction. Controller expect a retention of basic skills that could cause problems in case of system break downs.

The application of only one clearance of a whole trajectory for Class A aircraft without further intervention was significantly accepted.

Controllers significantly agreed that traffic could be handled safe in ORG 0 as well as in ORG 1 and ORG 2.

Same results were reached in asking if it was easy to keep aircraft well separated, but no significance could be reached for ORG 2. Here more difficulties are seen to keep separation in a Class A/Class B aircraft mix.

That the 'picture was maintained' was agreed significantly for all ORGs, but comments were given for ORG 2 like: 'system dictates me'.

Conflict detection and resolution was rated much less favourable (significant negative for ORG 0 because no conflict detection and resolution functionality was included).

The task partitioning between controllers was seen significantly positive (only not significant for pickup/planner in ORG 2 because the planner most of the time had nothing to do).

Significantly the controller negated that is was difficult to handle the traffic with the tools provided for all ORGs.

Personal work style was seen supported with ORG 0 significantly, with ORG 1 only in tendency (too many advisories), and ORG 2 was seen at least convenient with personal work style. Advisories and associated trajectories are not seen always as appropriate (trajectory solution vs. human solution was commented 'like two controllers working on the same area').

The controllers saw significantly no problem with PD/2 advanced concept when and how to interact with different classes of aircraft (A, B and manual).

14. CONCLUSIONS

The PHARE Demonstration 2 allowed controllers to explore a concept of an air-ground integrated arrival management in a paperless environment. Three different organisations for the management of arrivals were compared: A conventional handling with radar and flight plan information on paper supported by a basic arrival sequencing tool, an advanced concept for a ground system that does not need paper or electronic strips and that bases its planning on trajectories showing not only an arrival sequence and schedule but also solution and implementation support and a further developed air/ground integrated concept that can manage in addition airborne as well as ground based trajectories and allows a 4D-FMS and datalink equipped aircraft to implement its trajectory by its own. The three organisations are build on each other so that the new guidance modes are compatible with the one in use today. With only one week training the controllers were able to work with the advanced concepts in a stripless environment at least as well as with the conventional system.

The first results of the analysis of the measurements show that by working with the advanced concept in the TMA more traffic could be handled with lower flight times the traffic is delivered more precise with the same or even reduced workload. The variation between different controller teams in the management of arrival traffic became significantly reduced. The effect on the work of the ACC controllers working adjacent to TMA needs further investigations because the workload there can grow due to additional constraints in implementing a trajectory. The potential of further improvements by using trajectories close to the working style of the controllers with a minimum on necessary advisories became visible. A fast and reliable label interaction allowing a smooth working with a mouse driven system in a TMA is essential especially in high traffic. Conflict representation and solution support needs further developments to achieve the same level of acceptance as the advanced concept in general. The findings in PD/2 support that introduction of automated traffic of Class A aircraft will probably have the greatest potential in workload reduction and achievable precision. Special care on the retention of basic skill of the controllers and on the separation task between Class A and R/T guided traffic have to be taken into account when developing the concept towards a real system.

A significant acceptance of the advanced concept ideas by 32 active controllers of 7 different European nations with different background on their ATC systems as documented in the questionnaires as well as in the debriefing sessions is the most important result of the trials.

These findings support the future use of the concept as guideline for the development of future arrival management systems as part of new air traffic management systems.

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Optimal Resolution of En Route Conflicts

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Article $n^0 13$

Abstract

Automatic Control has been a subject of studies for the last twenty years. It involves many difficult problems that have to be solved: conflict detection, modelling of uncertainties on trajectories, clustering of 1-to-1 conflict to find unconnected n-aircraft problems, etc...

Moreover, the n-aircraft conflict resolution problem is highly combinatorial and cannot be optimally solved using classical mathematical optimization techniques. The set of admissible solutions is made of many unconnected subsets enclosing different local optima, but the subset enclosing the optimum cannot be found a priori.

In this paper, we present an automatic conflict solver and its implementation in an Air Traffic simulator, with statistical results on real traffic over France. This solver, which takes into account speed uncertainties and allows aircraft to fly on direct routes, solves every conflict on a loaded day, and gives each aircraft its requested flight level and departure time.

Introduction

As traffic keeps increasing, En Route capacity, especially in Europe, becomes a serious problem. Aircraft conflict resolution, and resolution monitoring, are still done manually by controllers. Solutions to conflicts are empirical and, whereas aircraft are highly automated and optimized systems, tools provided for Air Traffic Control (ATC) remain very basic. When comparing the current capacity and the standard separation to the size of controlled space, the conclusion is easy to draw: while ATC is overloaded, the sky is empty.

The need for an automatic problem solver is also a serious concern when addressing the issues of free flight. It is still very unclear how conflicts will be solved in free flight airspace. Human controllers frequently rely on standard routes and traffic organization for avoiding conflicts; they quickly become overloaded when controlling aircraft flying on direct routes. Free flight traffic, the aim of which is to permit each aircraft to fly its preferred trajectory, results in an unorganized structure, probably requiring automated, computer based, solvers. The Airborne Collision Avoidance System (ACAS) is certainly not a solution to the problem: it has only a limited view of the traffic, and moreover, should only be looked upon as a security system to prevent aircraft collision.

The first part of the paper presents the state of the art for problem solvers and discusses the constraints hypothesis and goals chosen. Modelling is introduced in the second part. Part three details the conflict solver. Part four presents examples of resolution on real traffic and statistical results.

*The LOG is a common laboratory of the Centre d'Etudes de la Navigation Aérienne and the Ecole Nationale de l'Aviation Civile

1 Automatic conflict resolution

1.1 State of the art

Conflict resolution is a very complex mathematical problem involving trajectory optimization and constraint handling. This problem has many facets: conflict detection, clustering, conflict resolution and optimality of the solution regarding different criteria. There have been many attempts to reach these objectives.

- AERA 3 [NFC+83, Nie89b, Nie89a] considered optimum results in the "Gentle-Strict" function for a two aircraft conflict, but the "Maneuver Option Manager" only searches for acceptable solutions and does not focus on the optimum. Moreover, the MOM behavior is poorly described and the way it handles n-aircraft conflict to divide them into problems that the GS algorithm can solve is unclear.

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

- Karim Zeghal [Zeg94], with reactive techniques for avoidance, gives a solution to the problem of automation which is robust to disturbance, but completely disregards optimization. Furthermore, the modelling adopted implies a complete automation of both on board and ground systems and requires speed regulation which cannot be handled by human pilots and would probably be very difficult to apply to aircraft engines without damaging them.
- ARC-2000 [K+89, FMT93] optimizes aircraft trajectories using 4 dimensional cones and priority rules between aircraft. Optimum is not reached, and the system relies on the availability of FMS-4D for all aircraft, with no uncertainty on speeds[1].
- A first approach to conflict resolution by stochastic optimization algorithms (genetic algorithms)[2] was done by Alliot and Gruber [AGS93]; more advanced results were presented in [DASF94b, DAN96]. Another approach, also using genetic algorithms, was tried by Kemenade, Hendriks, Hesseling and Kok [vKHHK95].

1.2 Specifications of the system

The main idea, guiding the design of the solver introduced in this paper, is to be as close as possible to the current ATC system:

Constraints: the solver has to handle the following constraints:

- Conflict free trajectories must respect both aircraft and pilot performances. Considering the evolution of ATC toward automation [DAM93], trajectories must remain simple for controllers to describe as well as for pilots to understand and follow.
- Trajectories must take into account uncertainties in aircraft speed due to winds, turbulence, unusual load, etc. Vertical speed uncertainties are particularly important.
- Maneuver orders must be given with an advance notice to the pilot. When a maneuver has begun, it must not be called into question.

Goals: We want to achieve the following goals:

- find conflict free trajectories
- Simultaneously minimize different criteria :
  1. the number of maneuver orders
  2. the conflict resolution duration
  3. the delay due to maneuvers
- compute these trajectories in real time.

[1] It must be noted that only the ARC-2000 system has been tested on "almost" real traffic.

[2] It must be noted that genetic algorithms were also applied to airspace sectorization with promising results [DASF94a].

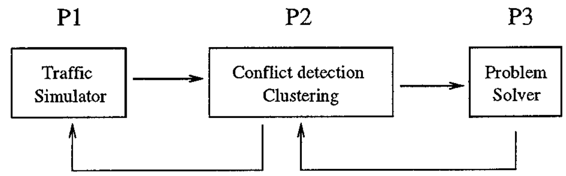

Figure 1: General architecture

2 Modelling

2.1 General architecture of the system

We just sketch here the architecture of the simulator; each part will be detailed in the following sections. The system architecture is presented in figure 1 and 2. The system relies on three main processes P1, P2, and P3:

- P1 is the traffic simulator.
- P2 is in charge of conflict pair detection, clustering of pairs, and verification of new trajectories built by the solver.
- P3 is the problem solver.

P1 sends current aircraft positions and flight plans to process P2. Process P2 builds trajectories forecast for T_w minutes, does conflict detection by pairs and transforms 1-to-1 conflicts in n-aircraft conflict. Then, process P3 (the problem solver) solves in parallel each cluster, as aircraft in each cluster are independent from aircraft in the other clusters. The problem solver sends to P2 new orders and P2 builds new trajectories forecast based on these orders. Then P2 once again runs a conflict detection process to check that modified trajectories for aircraft do not interfere with aircraft in another cluster, or with new aircraft. If no interference is found, new flight orders are sent to P1. If there are interferences, interfering clusters are joined and the problem solver is used again on that (these) cluster(s). The process is iterated until no interference between clusters remains, or no new aircraft is concerned by modified trajectories. The new orders are sent back to the traffic simulator.

The above process is iterated and all trajectories are optimized each δ minutes. However, during the computation

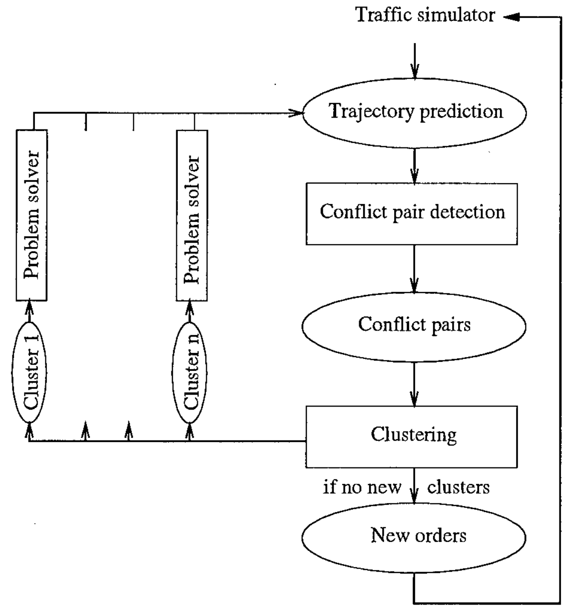

Figure 2: Detailed architecture of the prototype

time, aircraft are flying and must know if they must change their route or not. δ should be large enough to compute a solution, send it to the pilot and let him time enough to begin the maneuver. Consequently, for each aircraft, at the beginning of the current optimization, trajectories are determined by the previous run of the problem solver and cannot be changed for the next δ minutes.

2.2 The Air Traffic simulator

One of the main goals of this project was to test the algorithms on real traffic. The Air Traffic Simulator takes as input flight plans given by companies and pilots: no pre-regulation is done neither on departure time nor on requested flight levels. Consequently, flight plans only have to be deposited T_w minutes before take off.

The simulator uses a tabulated model for modelling aircraft performances: for a given aircraft type, it gives a vertical speed and a ground speed which depends on the aircraft attitude (whether it is climbing, leveled or descending). For example, a B747 leveled at FL-300 has a GS of 490 kts. If it is climbing, its GS will be 480 kts and its VS 1000 fts/mn. At FL-150, values would be respectively 430, 420 and 1800. Performance data comes from the French operational CAUTRA system. There are currently around 250 different aircraft models available.

All aircraft speeds are modified by a random value to take into account uncertainties on different factors (aircraft load, winds, etc...) This value can be either computed once at aircraft activation and remains the same for all the flight, or can be modified anytime during the flight. The conflict detector and the conflict solver are impervious to the way this value is computed as long as it remains inside a given interval. Uncertainty modelling for conflict detection and resolution is discussed later in the article.

Aircraft follow either classical routes (from way-point to way-point) or direct route (from the departure, or entry point in the French airspace to their destination or leaving point). The flight model is simple: an aircraft first climbs up to its RFL, then remains leveled till its top of descent, then descends to its destination.

Aircraft fly with a timestep that can be chosen at the start of the simulation. The timestep is always chosen in order to guarantee that two aircraft face to face flying at 500 kts could not cross without being closer than one standard separation at at least one timestep. For most of our simulation, we use a $15s$ timestep.

2.3 Conflict detection and clustering

2.3.1 Trajectory forecast and 1-to-1 conflict detection

As described above, the P2 process does trajectory prediction for T_w minutes. This trajectory prediction is done again by a simulation on a slightly modified version of the Air Traffic simulator. But, as stated above, we assume that there is an error about the aircraft's future location because of ground speed prediction uncertainties[3]. The uncertainties on climbing and descending rates are even more important. As the conflict free trajectory must be robust regarding these and many other uncertainties, an aircraft is represented by a point at the initial time. But the point becomes a line segment in the uncertainty direction (the speed direction here, see figure 3). The first point of the line "flies" at the maximum possible speed, and the last point at the minimum possible speed. When changing direction ($t = 4$), the segment becomes a parallelogram that increases in the speed direction. When changing a second time direction ($t = 7$), the parallelogram becomes an hexagon that increases in the new speed direction, and so on. To check the standard separation at time t, we compute the distance between the two polygons modelling the aircraft positions and compare it to the standard separation at each timestep of the simulation.

In the vertical plane, we use a cylindrical modelling (figure 3). Each aircraft has a mean altitude, a maximal altitude and a minimal altitude. To check if two aircraft are in conflict, the minimal altitude of the higher aircraft is compared to the maximal altitude of the lower aircraft.

[3]Uncertainties on ground track will not be considered, as they do not increase with time and will be included in the standard separation

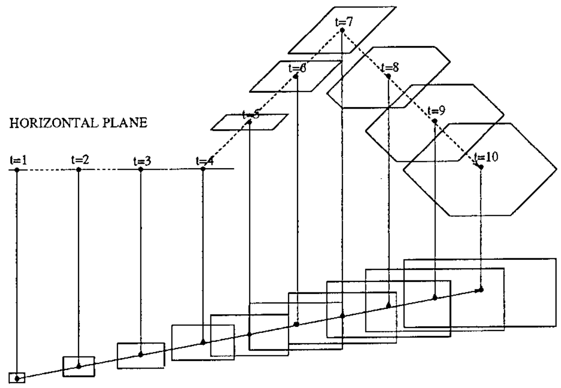

Figure 3: Modelling of speed uncertainties.

Let's take an example. A B747 is leaving its departing airport (altitude 0) at $t = 0$. Its climb rate is 1800 fts/mn and its gspeed is 175 kts. If we suppose that gspeed uncertainty is 5% and vspeed uncertainty 20%, maximal and minimal climb rate are $1800 \times 1.2 = 2160$fts and $1800 \times 0.8 = 1440$ fts/mn and gspeeds are respectively 184 and 166 kts. This means that $15s$ later, the fastest and higher point has traveled 0.76 Nm and 540 fts while the slowest and lowest has only traveled 0.69 Nm and 360 fts. But this time, when computing maximal and minimal speeds, the difference of altitude of both points must be taken into account. At 540 fts, the tabulated model gives a standard gspeed of 197 kts, so max gspeed is $197 \times 1.2 = 237$ kts. At 360 fts, standard gspeed is 189 kts, with a minimal gspeed of 151 kts. So, the size of the convex grows much faster than the 20% factor for some aircraft.

Duration T_w can be changed, but must be at least equal to $2\times\delta$. A good evaluation of T_w is difficult. With a perfect trajectory prediction, the larger T_w, the better. However, this is not true as soon as uncertainties are included in the model. A large value of T_w induces a large number of 1-to-1 conflict, as sizes of convexes modelling aircraft positions grow quickly with time. Therefore, the conflict solver can become saturated.

2.3.2 Clustering

After pair detection, P2 does a clustering which is a transitive closing on all pairs. Each equivalence class for the relation "is in conflict with", is a cluster.

For example, if aircraft A, B are in conflict in the T_w window, and if B is also in conflict with C in the same time window, then A, B, C is the same cluster and will be solved globally by the conflict solver.

The conflict solver sends back to P2 maneuvers orders for solving conflicts. Then P2 computes new trajectories for all aircraft and checks if new interferences appear. For example, if the new trajectory given to aircraft B to solve conflict with A and C interferes with cluster D, E and with aircraft F, then A, B, C, D, E, F will be sent back to the problem solver as one conflict to solve.

The process will always converge: in the worst case, P3 will have to solve a very large cluster including all aircraft present in the next T_w minutes. However, this technique is usually efficient as a very large number of clusters can be solved very quickly in parallel.

3 The conflict solver

3.1 Theoretical results

The two aircraft conflict problem has been widely studied theoretically using Optimal Command Theory.

Optimal Command Theory with State Constraints ([E.K82]), lead to the following conclusions exposed by Durand, Alech, Alliot and Schœnauer in [DAAS94]. For a conflict resolution involving two aircraft: at the optimum, as long as the standard separation constraint is not saturated, aircraft fly in straight lines. When saturating, aircraft start turning, and as soon as the separation constraint is over, aircraft fly straight again. This result can easily be extended to the case of n aircraft, with $n \geq 2$. When moving only one aircraft, it can be proved (see [Dur96]) that trajectories are regular (they do not include any discontinuous point).

Numerical resolutions show that the length of the conflict free trajectory increases when:

- the angle of incidence between the two aircraft decreases.
- the speed ratio gets close to 1.
- aircraft are closer to the conflict point.

The previous mathematical study leads naturally to simplify the conflict free trajectory (see figure 4). The turning point trajectory is very close to the optimal trajectory and much simpler to describe. It will be used in the following.

It can also be mathematically proved that if aircraft parameters (speed and heading) are constant at intervals, and if aircraft trajectories don't loop, the set of conflict free trajectories has two connected components. In one of the two sets, one of the aircraft always passes the other one on its right side, whereas in the other set, it passes it on its left side. For n aircraft, the theoretical number of conflict free trajectories sets expands to $2^{\frac{n(n-1)}{2}}$: if $n = 9$, there is more than 268 million possibilities (see [MDA94]).

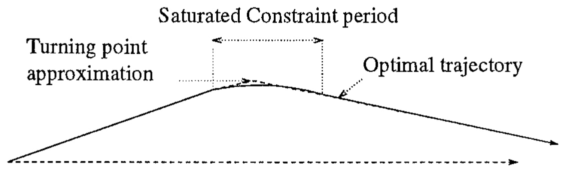

Figure 4: Turning point approximation.

3.2 Maneuver decision time

Because of uncertainties, a conflict that is detected early before it should occur may finally not happen. Consequently, deciding to move an aircraft in that case could sometimes be useless, and could even generate other conflicts that would not occur if no maneuver had been decided. This explains why controllers do not solve conflicts too early. With the turning point modelling, when there is no uncertainty, the earlier the maneuver is started, the lower the delay. However, if speed is not strictly maintained, the earlier the conflict is detected, the lower the probability it will actually happen. Thus, a compromise must be reached between the delay generated and the risk of conflict.

3.3 Choosing the model

In this paper, it was decided to allow direct routes to aircraft. In a first time, only turning points were considered in the horizontal plane. After the turning point execution, aircraft were directed to their destination.

If we do not want to call into question previous maneuvers and be able to solve very large conflicts, we must try to start maneuvers as late as possible with respect to the aircraft constraints. This argument is enforced by the fact that we allow aircraft to have large uncertainties on their speeds[4].

For example, the first trajectory of figure 5, at $t = 0$, cannot be modified before $t = \delta$. At the end of the first optimization run, at $t = \delta$, the current position of the aircraft is updated. The maneuver that occurred between $t = \delta$ and $t = 2\delta$ is kept as a constraint for the second optimization run (on the example, no maneuver is decided). In the above example, we can see that the maneuver described on line 2 (resulting from an optimization at $t = \delta$) is more penalizing than the maneuver described on line 3 (resulting from an optimization at $t = 2\delta$). This phenomenon occurs

[4] We do not plan to solve conflicts by speed modifications. Theoretical study shows that optimal En Route conflict resolution by speed modifications would require large anticipation time (anticipation time depends on different parameters such as angle of convergence, speed margins for each aircraft, standard separation etc; more details can be found in [Dur96]). This is quite unrealistic due to aircraft speed uncertainties.

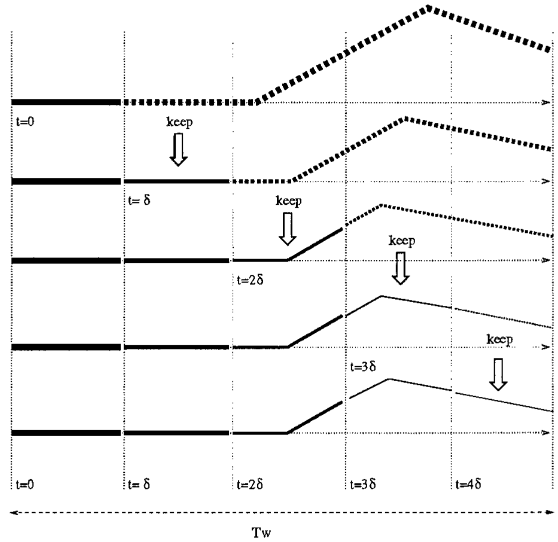

Figure 5: The model and real time optimization.

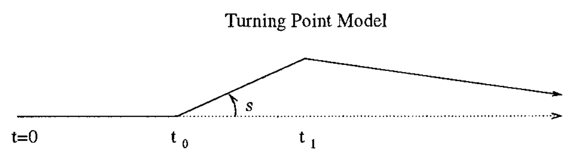

Figure 6: Horizontal maneuver modelling.

because of uncertainties. If uncertainties on speed are important, having a small δ will be very helpful to minimize the resolution costs in the real time situation.

Pilots should only be given maneuver orders that will not be modified; if no conflict occurs, no order will be given.

The turning point angle will be 10, 20 or 30 degrees. The previous elements lead us to choose the following model (figure 6). A maneuver will be determined by:

- the maneuver starting time t_0.
- the turning point time t_1.
- the deviation angle s.

In a second time, vertical maneuvers were introduced. Therefore, the aircraft trajectory is divided in 4 periods (figure 7):

- Climbing period. In this period, aircraft can be leveled at a lower than requested flight level during a moment to resolve a conflict. The maneuver starts at t_0. Aircraft start climbing again at t_1 and $s = 0$.

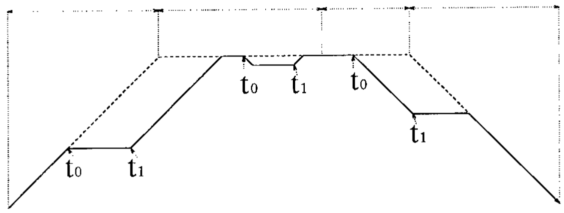

Figure 7: Vertical maneuver modelling.

- Cruising period. When aircraft have reached their desired flight level, they may be moved to the nearest lower level to resolve a conflict. Aircraft start descending at t_0 and start climbing at t_1 $(s = 0)$.
- End of Cruising period. When aircraft are about 50 nautic miles from beginning their descent to destination, they may be moved to a lower level to resolve a conflict. Aircraft start descending at t_0 and are leveled at t_1 $(s = 0)$.
- Descending period. During this period no vertical maneuver is possible.

No maneuver will be simultaneously done in the horizontal and vertical plane. This model has the great advantage of reducing the size of the problem. In order to solve conflict due to aircraft taking off or entering the airspace simultaneously at the same point, a variable of delay t_d is introduced.

For a conflict involving n aircraft, the dimension of the search space is $4\,n$. This will allow us to solve very difficult conflicts with many aircraft without investigating a large solution space.

3.4 Complexity of the problem

The complexity of the problem is exposed by Medioni, Durand and Alliot in [Dur96]. Let's consider a conflict between two aircraft. We can easily prove that the minimized function is convex, but the set of conflict free trajectories is not. It is not even connected. If trajectories don't loop, the set of conflict free trajectories has two connected components. For a conflict involving n aircraft there may be $2^{\frac{n(n-1)}{2}}$ connected components in the free trajectory space which strongly suggests that any method which requires exploring every connected component is NP[5]. It is important to note that this complexity is independent of the modelling chosen (see [Dur96]).

[5] A Non deterministic Polynomial (NP) problem belongs to a class of problem for which there are no polynomial-time algorithm known to solve the problem.

3.5 The function to optimize

One of the principal algorithm design challenges is to define a suitable function to optimize. A multiple-criteria function is required that simultaneously attempts to:

- minimize the delay due to deviations imposed on aircraft.
- minimize the total number of resolution maneuvers required and the total number of aircraft that will be moved[6].
- minimize the maneuver duration so that aircraft are freed as soon as possible for maneuvers that may be necessary subsequently.
- enforce all separation constraints between aircraft.

Instead of considering a single scalar value that takes into account the different lengthenings of trajectories, the number of maneuvers and the conflicts between the aircraft, the contributions from each separate aircraft pair are maintained in a matrix F of size $n \times n$ (where n is the number of aircraft):

- If $i < j$, $F_{i,j}$ measures the conflict between aircraft i and j in the optimization time window T_w. It is set to 0 if no conflict occurs in this period and increases with the severity of the conflict. At each time step t, we compute $C_{t,i,j}$ as the difference (when positive) of the standard separation and the distance between the polygons i and j describing aircraft i and j position at time t. These values are added and give a measure of the conflict between i and j.

$$F_{i,j} = \sum_{t=0}^{total\,time} (C_{t,i,j})$$

- If $i > j$, $F_{i,j}$ measures the efficiency of the resolution between aircraft i and j. It is set to 0 if no conflict can happen between i and j after the optimization time window T_w. If a conflict may remain after this period, $F_{i,j}$ gives a bad mark to pairs of aircraft for which the difference of heading and speed are small (these conflicts are difficult to solve).
- $F_{i,i}$ (see equation 1,2,3) measures the takeoff (or entering) delay given to aircraft i (C_d is a constant), the maneuver duration time $(t_1 - t_0)$ and trajectory lengthening (C_s is a constant depending on the maneuver angle s), and the number of maneuvers (C_m is

[6] Thus, instead of sharing the global delay on all the aircraft, some aircraft will support a part of the delay and others will not.

a constant multiplied by 1 if a maneuver is supposed to become definitive and 0 if not):

$$\begin{aligned} F_{i,i} &= C_d\, t_d & (1)\\ &+ C_s\,(t_1 - t_0) & (2)\\ &+ C_m\,[(t_0 \leq 2\,\delta)\,\&\,(t_1 > t_0)] & (3)\end{aligned}$$

This matrix contains much more information than a scalar global value F, and is useful in the optimization algorithm used.

However, a global scalar value is required, and can be defined as follows:

$$\begin{aligned} \exists(i,j),\ i \neq j,\ F_{i,j} \neq 0 \Rightarrow F &= \frac{1}{2 + \sum_{i \neq j} F_{i,j}} \\ \forall(i,j),\ i \neq j,\ F_{i,j} = 0 \Rightarrow F &= \frac{1}{2} + \frac{1}{2 + \sum_{i \geq j} F_{i,j}} \end{aligned}$$

The choice of this function guarantees that if the value is larger[7] than $\frac{1}{2}$, no conflict occurs in the optimization time window. If a conflict remains, the function does not take into account the delays induced by maneuvers. When the value is smaller than $\frac{1}{2}$, maximizing the function minimizes the remaining conflicts. When the value is larger than $\frac{1}{2}$, maximizing the function minimizes the possible remaining conflicts after the optimization time window, the number of maneuvers, their duration, and the delays induced by maneuvers. When no conflict and no maneuver occurs, the function is equal to 1.

3.6 A global optimization problem

Use of local methods, such as gradient for example, is useless here, because these methods rely on the arbitrary choice of a starting point. Each connected component may contain one or several local optima, and we can easily understand that the choice of the starting point in one of these components cannot lead by a local method to an optimum in another component. We can thus expect only a local optimum.

3.7 Genetic Algorithms applied to conflict resolution

Genetic algorithms (GAs) are global stochastic optimization technics that mimic natural evolution. They were initially developed by John Holland [Hol75] in the sixties. The subject of this paper is not GAs and the interested reader should read the appropriate literature on the subject [Gol89]. The general principles are given on figure 8.

[7] Our priority is to find trajectories without conflict.

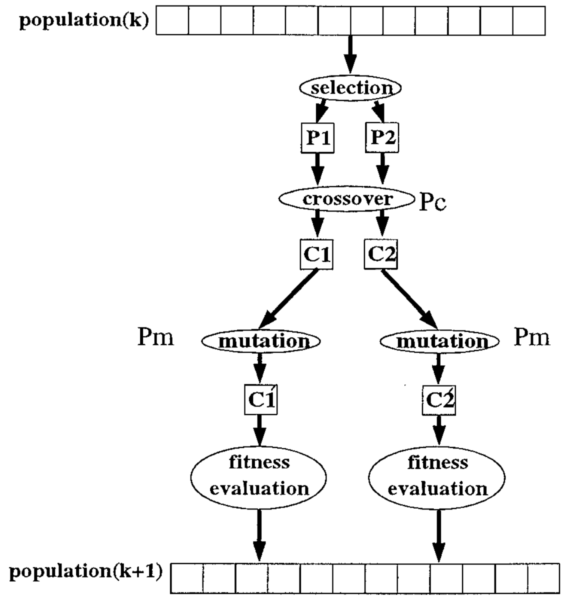

Figure 8: GA principle

Genetic algorithms are a very powerful tool, because they do not require much information and are able to find many different optima that can be presented to a human operator.

Moreover, we know much about the function to optimize and this information can be used to create adapted crossover [DAN96] and mutation operators, an other advantage of GAs over other optimization technics.

Genetic algorithms are very efficient for solving global combinatorial optimization problems but are not very efficient for solving local searches with a good precision. Consequently, in the last generation of the genetic algorithm, a local optimization method is used to improve the best solution of each chromosome class defined above: a simple hill-climbing algorithm is applied to the best chromosomes at the end of the GA run.

4 Results

We present here examples of resolution that illustrate[8] the performance of the algorithm. These examples were computed on a Pentium 200. In the following, the time window for prediction is fixed at 12 minutes ($T_w = 12$ mn) and an optimization is computed every 3 minutes ($\delta = 3$ mn).

[8] The label gives the number of the aircraft, its heading, its flight level and its horizontal speed

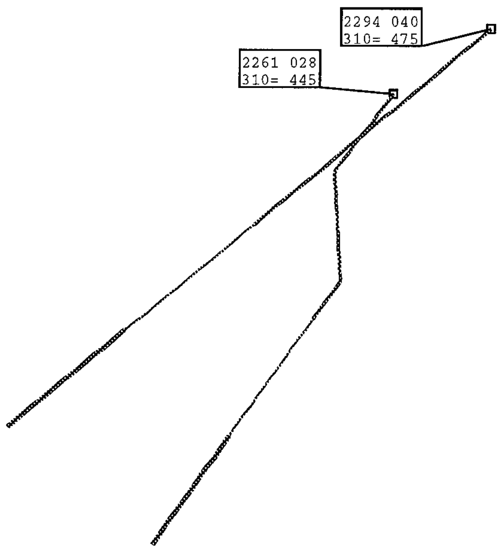

Figure 9: Conflict resolution at time 09:36:00 UT

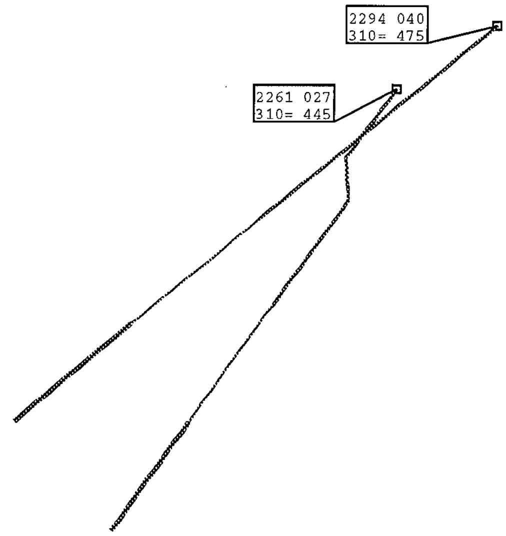

Figure 10: Conflict resolution at time 09:39:00 UT

4.1 Example of Two-Aircraft Conflict

In this first application, at 09:36:00 UT a conflict is detected between two aircraft numbered 2294 and 2261 flying at level 310 (see figure 9). Because of uncertainties, the horizontal predicted speed of aircraft 2294 is 475 kts plus or minus 5% (its real speed is 470 kts), whereas the horizontal predicted speed of aircraft 2261 is 445 kts plus or minus 5% (its real speed is 427 kts). The solver calculates the optimal solution to solve the conflict in the horizontal plane: aircraft 2261 should be moved 30 degrees left at 09:43:00 UT during 2 minutes and 15 seconds. As only maneuver orders starting before 09:39:00 UT are definitive, no order is given to aircraft 2261.

At 09:39:00 UT (figure 10), the conflict is still detected, however, the solver suggests to move aircraft 2261 of 30 degrees left at 09:47:45 UT during 45 seconds only. As only maneuver orders starting before 09:42:00 UT are definitive, no order is given to aircraft number 2261.

At 09:42:00 UT, no conflict is detected between these two aircraft.

Because of uncertainties, the initial optimized trajectory requires a fairly large deviation from the intended path. As times goes on, aircraft are closer to the conflict point, uncertainty decreases, and the optimized trajectories give smaller deviations. Finally, at 09:42:00 UT, the conflict disappears.

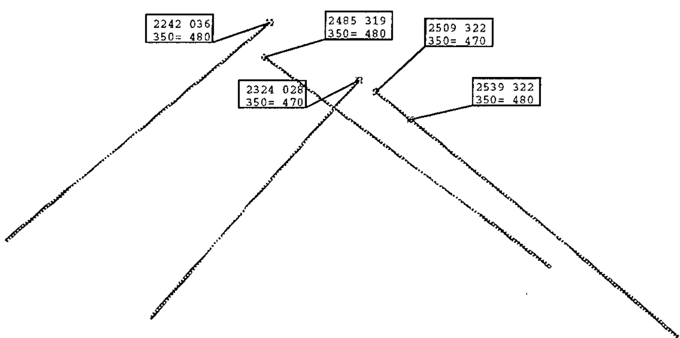

Figure 11: 10:33 UT - 5 aircraft conflict before resolution

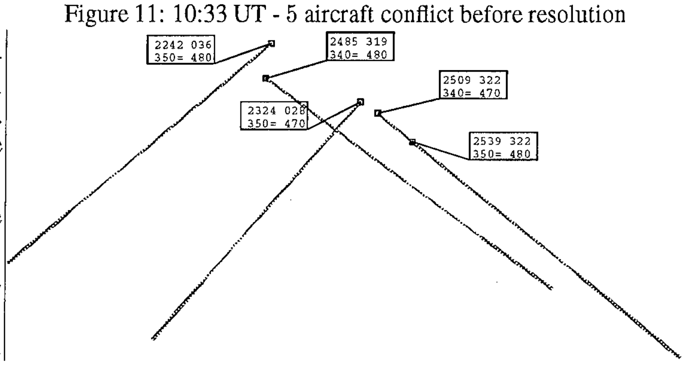

Figure 12: 10:33 UT - 5 aircraft conflict after resolution

aircraft	beginning	ending
$2509 - 2539$	$10:40:00$	$10:45:00$
$2324 - 2485$	$10:42:00$	$10:43:00$
$2324 - 2509$	$10:44:00$	$10:45:00$
$2242 - 2485$	$10:44:00$	$10:45:00$

Table 1: 10:33 UT - Conflict beginning and ending

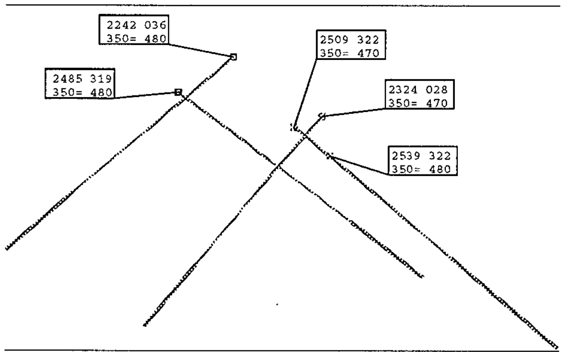

Figure 13: 10:36 UT - 5 aircraft conflict before resolution

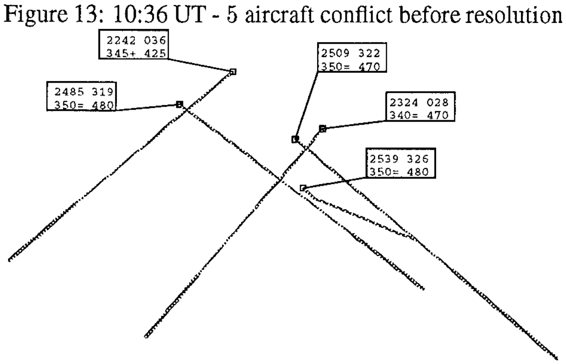

Figure 14: 10:36 UT - 5 aircraft conflict after resolution

4.2 Complex conflict involving 5 aircraft

In this example (figure12), at 10:33:00 UT, 5 aircraft are cruising at FL-350. 4 1-to-1 conflicts are detected (see table 1).

Only 2 aircraft are moved as follows: aircraft 2509 is first moved vertically at 10:39:15 UT to FL-340 till the end of the time window (10:45:00 UT), which resolves conflicts with aircraft 2539 and 2324. Aircraft 2485 is moved vertically at 10:41:15 UT to FL-340 till the end of the time window, which resolves conflicts with aircraft 2242 and 2324.

No aircraft is given an order at this step (no maneuver is supposed to start before 10:39:00 UT).

At 10:36:00 UT (figure12), 5 conflicts are detected (table 2).

aircraft	beginning	ending
$2324 - 2485$	$10:42:15$	$10:43:00$
$2509 - 2539$	$10:42:30$	$10:48:00$
$2324 - 2509$	$10:44:00$	$10:46:15$
$2242 - 2485$	$10:44:15$	$10:45:00$
$2324 - 2539$	$10:45:15$	$10:46:15$

Table 2: 10:36 UT - Conflict beginning and ending

The previous solution is not conflict free anymore because of the new 1-to-1 conflict that has appeared at time 10:45:15 UT between aircraft 2324 and 2539. The solver finds another solution. Only 3 aircraft are moved as follows: aircraft 2324 is first moved vertically at 10:41:30 UT to FL-340 during $4mn30s$, which resolves conflicts with aircraft 2485, 2509 and 2539. Aircraft 2539 is moved 20 degrees left at 10:42:00 UT during $3mn$, which resolves conflict with aircraft 2509. Finally, aircraft 2242 is moved vertically at 10:43:30 UT to FL-340 during $1mn30s$, which resolves the conflict with aircraft 2485.

Only aircraft 2324 will be given a maneuver order at this step because its maneuver will be definitive at the next iteration. Its maneuver ending and the other maneuvers will be reconsidered at time 10:39:00 UT.

At time 10:39:00 UT, 2 unconnected clusters (2324, 2509, 2539) and (2485, 2242) are found.

Aircraft 2324 finally ends its maneuver at 10:45:30 UT. Aircraft 2539 is moved 10^0 left at 10:43:30 UT during $7mn$. Aircraft 2485 is moved vertically to FL-340 at 10:44:00 UT during $45s$, which definitely resolves conflict with aircraft 2242.

4.3 Example with large numbers of Conflicting Aircraft

Figure 15 gives an example of a 27 aircraft cluster. It is here useless to try to understand what happens, but every conflict is resolved.

4.4 A complete test

Testing of the problem solver is still in progress, but some tests have already been completed [Cha95]. A complete experiment done with unregulated flight plans of the 21th of June 1996 is described here. It involves 6388 aircraft over France. Uncertainties on climbing rate and ground speed are respectively set to 20% and 5%, and standard separations are set to 6 nm and 1000 feet. The experiment is run under the Direct Route hypothesis (aircraft are allowed to go directly to their destination). We only detect

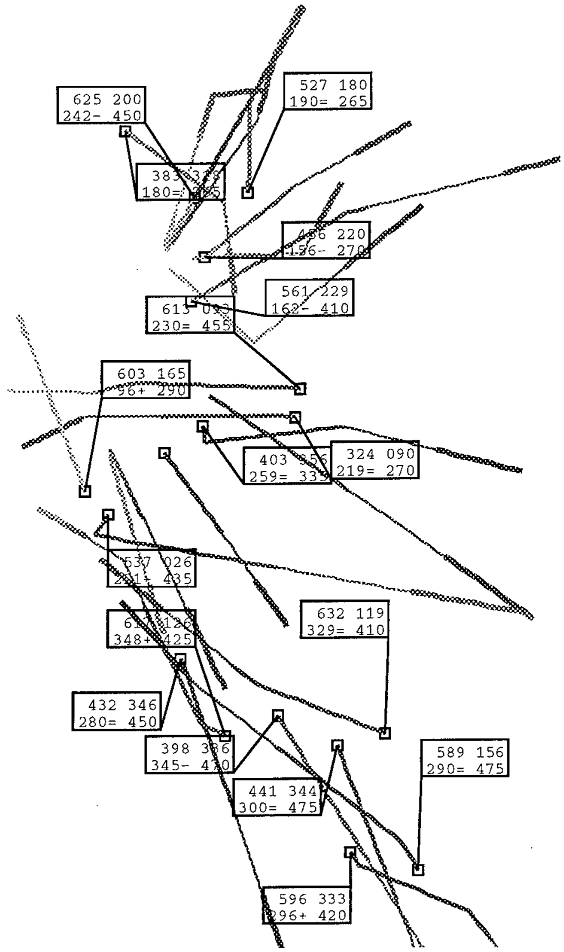

Figure 15: 27 aircraft cluster

and solve conflicts above 10000 feet, as we are only interested in En Route conflicts. Aircraft entering Paris TMA control area are sequenced on the TMA entry points, but no control is done inside the TMA.

When running this one day test with a very basic conflict detection algorithm (only actual conflicts are detected, with no uncertainty on speed) and with no conflict resolution, 1649 conflicts are detected.

When running the complete simulation with detection and resolution, fixing $\delta = 3$ minutes and $T_w = 12$ minutes, the P2 process detects 5064 1-to-1 different conflicts (This means that a detected conflict has $\frac{1649}{5064} = 32.6\%$ chance to really occur. The problem solver resolves 9130 clusters of different sizes (table 3). There are 4155 clusters including different sets of aircraft. There is no unsolved cluster and consequently no conflict remains.

Only 1687 aircraft are given 2200 maneuvers which represents 1.3 maneuver per aircraft. The mean duration of a maneuver is $2mn23s$. Details on maneuvers are given in table 4.

clus size		clus size		clus size	
2	6448	10	23	18	1
3	1539	11	23	26	1
4	570	12	17	27	1
5	210	13	7	28	1
6	126	14	7	31	1
7	67	15	5	32	1
8	48	16	5		
9	28	17	1	total	9130

Table 3: Sizes of solved clusters.

type	number	mean duration	max duration
vert	1256	2mn 22s	15mn 45s
10^0	218	2mn 14s	8mn 45s
20^0	452	2mn 14s	12mn 30s
30^0	274	2mn 38s	8mn 45s

Table 4: Maneuvers repartition.

1337 aircraft are delayed before taking off or entering the French airspace. For these aircraft, the mean take off or entering delay is $2mn56s$ (maximum $6mn$). The global mean take off or entering delay is $37s$.

The mean maneuver duration expectation per aircraft is $49s$ which represents 1.79% of the flight duration.

The mean flight duration is $45mn54s$ before resolution and $45mn58s$ after resolution. The mean delay caused by maneuvers is $4s$. Only 934 aircraft are delayed because of maneuvers (most of the aircraft moved in the vertical plane are not delayed). The maximum delay is $4mn$ and the mean delay (for aircraft delayed) is $29s$.

The same simulation, with the same parameters was performed without giving maneuvers in the vertical plane. 5112 different 1-to-1 conflicts are detected. The problem solver resolves 8869 clusters of different sizes (table 5). There are 4115 clusters including different sets of aircraft. There are 2 unsolved clusters involving 52 and 64 aircraft, but remaining conflicts are resolved at the next step. At last, no conflict remains.

Only 1779 aircraft are given 2344 maneuvers which represents 1.32 maneuver per aircraft. The mean duration of a maneuver is $2mn35s$. Details on maneuvers are given in table 6.

1300 aircraft are delayed before taking off or entering the French airspace. For these aircraft, the mean take off

clus size		clus size		clus size	
2	6269	12	14	24	1
3	1440	13	4	25	1
4	548	14	4	46	1
5	244	15	7	48	2
6	133	16	5	50	1
7	79	17	3	52	1
8	46	18	3	55	1
9	26	19	2	59	1
10	17	20	1	63	1
11	12	22	1	64	1
				total	8869

Table 5: Sizes of solved clusters (horizontal maneuvers).

type	number	mean duration	max duration
10^0	518	2mn 11s	17mn 45s
20^0	934	2mn 22s	21mn 30s
30^0	892	3mn 1s	25mn 30s

Table 6: Maneuver repartition.

or entering delay is $2mn55s$ (maximum $6mn$). The global mean take off or entering delay is $35s$.

The mean maneuver duration expectation per aircraft is $57s$ which represents 2.07% of the flight duration.

The mean flight duration is $45mn54s$ before resolution and $46mn3s$ after resolution. The mean delay caused by maneuvers is $9s$. Some maneuvered aircraft are not delayed (a 10^0 maneuver during $1mn$ induces $1s$ of delay). The maximum delay is $13mn45s$ and the mean delay (for the 1269 aircraft delayed) is $41s$.

4.5 Limitations and improvements

The solver has different limitations. First of all, it is designed to handle En-Route control problems, with a large number of aircraft and a time window larger than 10 minutes. Even if it could perform resolution for a smaller number of aircraft and a shorter time window, we are currently investigating other algorithms, based on the A^* family and on interval programming that are probably much more fitted when considering problems linked to, for example, ASAS. The conflict detection system, that relies on a simulation of trajectories for the next T_w minutes, and thus prevents using combinatorial linear programming, could also be simplified for shorter time windows. Approximating an aircraft trajectory by linear segments is useless on 12 minutes, but could be considered for less than 5 minutes.

One of the main problems that remains to be addressed is certainly trajectory forecast. The system is highly sensitive to errors on aircraft speed. Indeed, the cluster size increases when T_w increases and when the uncertainty on speed increases. For example, with the uncertainty on speed estimation used in the above examples and $T_w = 15$ mn, the biggest cluster deals with 56 aircraft; with $T_w = 16$ mn, it reaches 71 aircraft. The solver could then quickly saturate. Trajectory forecast is definitely a serious issue for all systems doing either automatic resolution or controller assistance: no controller would accept an operational system which detects conflicts that never occur, or fails to detect conflicts that will occur. Work is in progress to improve dynamically aircraft trajectory forecast using the "standard" aircraft model and its past positions, based on neuro-mimetics technics and mathematical regressions.

To prevent clusters to become too large, another possibility is to forbid cluster merging after resolution by making new resolution with aircraft in one cluster being constraints for aircraft in the other cluster. Global optimality would be lost, but it would allow to increase the detection time window or uncertainty.

Other improvements are currently under development: introduction of time maneuver execution uncertainty, military zones, indirect routes, etc. We also plan to run many tests and statistics with different parameters (standard separation) and other traffic data, especially with projection for the future.

5 Conclusion

The conflict solver introduced in this paper is a step toward automatic resolution of en route conflicts. The goal of this work was to show that a scientific, mathematical approach along with a serious algorithmic design could build a complete system for conflict detection and resolution, that would still remain small in size (the whole system including the traffic simulator, conflict detection, clustering and problem solver is less than 4500 lines of code). Even if many improvements have to be done, the results of the simulation are good. Mean delays induced by maneuvers are very short (4 s), maximum en route delays remains also short (4 mn) and all these results were obtained with unregulated flight plans.

Trying this system on real traffic, to develop resolution tools, or for night control, would be an interesting challenge, but is more a political than a technical problem.

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Global Air Traffic Management (GATM)

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SUMMARY

The paper describes concepts that relate to Global Air Traffic Management emphasizing the potential of mathematical modeling and behavioral simulation in creating a flexible and efficient traffic management system.

These concepts include design methodology, flow management, airspace structure and optimal runway scheduling. They reflect the author's theoretical study and experience on the subject of Air Traffic Control, combining knowledge and ideas from related large scale optimal dynamic resource allocation problems encountered in military logistics, transportation and economics.

The resource in question is the airspace-time and the paper discusses alternative ways, such as the space-time market, for sharing it in a safe, expedient and cost effective way.

The paper concludes with optimal runway capacity results for the two major airports of Frankfurt and Chicago O' Hare.

1. INTRODUCTION

The phenomenal worldwide growth in Air Transport presents challenging problems in assuring safe and reliable transportation for passengers and freight. Delays at European and US airports increased significantly in the last decade, and several airports face severe congestion problems. This trend is likely to continue in the future, due to the deregulation of air travel, rendering traditional Air Traffic Control (ATC) practice inadequate.

Efforts to improve the system have been made by respected organizations such as NATO-AGARD, FAA, NASA, Transportation Systems Center, the MITRE Co., the Massachusetts Institute of Technology etc., in the US and EUROCONTROL, the Commission of European Communities, DLR and a number national authorities and institutes in Europe.

This paper presents concepts relating to Global Air Traffic Management (GATM) focusing on mathematical modeling aspects.

The GATM is viewed as a dynamic resource allocation problem. Centralizing the information about user intent enables GATM to allot flights safe space-time (which the "resource" in question) by resolving contention for the same slice of the resource. It is called dynamic because it has to respond to stochastic (random) changes in weather and user intent.

Following a brief account of the background, we analyze its objective and present two complementary views of GATM, namely:

- GATM: a space-time reservation system, and
- GATM: a market for the space-time resource, whereby, digital brokers residing in the network of connected ground computers auction the use of the space time resource on behalf of the airlines.

One may recall that much of the criticism of computer skeptics owes to the inability of early automation to adapt to unexpected circumstances, whereby, instead of changing the initial plan, one tried to return to it at any cost.

This brings up the issues of adaptability and generality. The latter facilitates the former. Borrowing from computer science, GATM, has to provide a general system description language that will allow it to take on any form, so as to be able to evolve with changing circumstances. This "chameleon" GATM will be able to take up any form, even that of the system as we know it today; this could provide a useful benchmark for comparisons. In computer science terms, the present system is an instance of the generalized GATM. Transformability will answer the question of transition from one system deployment to another.

The paper further analyzes the issues of airspace structure, airport runway scheduling and flow management that seeks to coordinate the individual airport runway scheduling activities.

The tools used by the author, in his quest to understand GATM, is TMSIM, an experimental traffic management simulation whose initial purpose was to visualize the function of the runway scheduling algorithm developed in his doctoral dissertation.

Adding route structure to connect airports, a light weight model of flight, and following the object oriented programming paradigm TMSIM produces a convincing replica of the ATC world, thereby giving the opportunity to examine individual component function and performance within a global system context and from both strategic / macroscopic and tactical / microscopic points of view.

We present sample results from a runway capacity study concerning two major airports, namely the Chicago O' Hare and the Frankfurt (EDDF), illustrating the effects of optimal runway scheduling that was carried out using TMSIM with a days worth of real traffic data.

The lesson from TMSIM, is that GATM has to be "fertilized in vitro", in the controlled environment of a numerical experimentation facility that would invite contributions from the academic research, industrial and ATC operational communities, leading up to the creation of a reservoir of collective wisdom (i.e. libraries of ATC objects) distributed over the Internet.

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

2. BACKGROUND

2.1 Limitations Of Traditional Air Traffic Management (ATM)

ATC started when there were few aircraft and no computers. It was designed by aerodynamics specialists whose primary concern was aircraft design. Naturally, it has a strong fluid mechanics "Control Volume" flavor, with emphasis on accurate avionics, surveillance and communication technologies. Its evolution has been driven by emerging needs and technologies, adding patches to the "existing".

It is becoming increasingly clear that this course of "coral colony" evolution has reached its limits. It remains to revise "old fashion" decision making practice to fully exploit the benefits of modern science and technology.

One of the main barriers to change has been the mistrust against computer automation and efficient adaptive modeling, both of which are relatively recent. This mistrust has deprived ATC from a harvest of brilliant ideas that would exploit the potential of modern TELEMATICS (information and communications technologies).

2.2 Simulations

Simulation is an extremely useful experimentation tool in the hands of researchers, as it allows them to clarify concepts, visualize the results and evaluate modes of operation.

Most of the emphasis in existing large scale ATC simulations is placed in detailed modeling of aircraft dynamics and accurate replication of the current system's facilities and equipment, as they exists today. This type of simulation is geared mainly towards training and requires immense efforts in setting up. It certainly is a very expensive way of studying ATM on a global scale.

Another type of popular simulation is that of a differential equation which, based on simplifying assumptions, implements a set of mathematical relations between quantified system characteristics. This type of simulation is useful as an alternative to statistical regression in order to extrapolate into the future.

What is proposed herein is a "light weight" flexible behavioral simulation tool with a user-friendly interface that would run on a network of UNIX workstations.

2.3 Research

The main thrust of the research so far has been placed on technologies for avionics, guidance, radar, global positioning systems (GPS) etc. However, future ATM design has been guided "ad hoc", by ATC operational experience and a gross balancing of national and commercial interest.

However, there have been bright spots, if only at the level of basic research, concerned with GATM strategies that are working in the right direction. Such an example of rigorous work with sound theoretical foundation, without compromising creativity, is carried out, among other places, at the Flight Transportation Laboratory of the Massachusetts Institute of Technology (FTL-MIT), on safety analysis, flow management optimal runway scheduling and other related ATM issues.

3. METHODOLOGY

3.1 Top Down Design

Living with a system makes one often loose perspective. The system becomes the horizon and we are unable to look behind it. Top down design seeks to relieve us from the preoccupation of current practice, thus enabling:

- a systematic and comprehensive analysis and prioritization of needs and objectives
- the identification of component functionality and relationships
- structured synthesis using modern methodology, technologies and scientific results

The hierarchical tree structure representing functional breakdown, i.e. the workspace of top-down design, requires several refinement and tuning iterations. This necessitates rigorous mathematical modeling that allows for:

a) quantification of system parameters and criteria in order to effectively evaluate alternative means of management and control

b) visualization that brings out hidden aspects and misconceptions about the ATC/ATM functionality, clarifying concepts and inspiring new solutions.

c) understanding the potential and the limits of modern technology

3.2 Design Flexibility

One may recall from the late nineteen-seventies, when computer literacy was just beginning, how novices used to hardwire data in their computer programs.

Just like computers are now using configuration resources, one has to impart to a GATM system the flexibility to transform by tuning of parameters. This way GATM will manifest itself according to the prevailing conditions within each given geographic context. Such conditions may pertain, for example, to climate or national sovereignty.

Similarly, GATM should also be able to track automatically the shifting patterns of demand for air-transport and have provisions for accommodating new technologies and equipment in a "plug and play" fashion, to borrow again a trendy expression.

3.3 Analogies and Intuition

It is often the case in mathematics that the solution to a problem is simply the way you look at it. For instance, runway scheduling, i.e. putting aircraft in the optimal landing sequence, may be viewed as the problem of finding a minimum length tour of cities for a Traveling Salesman, the notorious TSP.

Analogies improve intuition and creativity; they assist human thought process by making abstract notions tan-

gible, and they allow faculties of engineering to borrow from each other.

The main analogies drawn in this paper are the:

1. Space-Time Resource Allocation System
2. Space-Time Reservation System
3. Space -Time Stock-market with Digital Brokers

3.4 Dynamic Space-Time Resource Allocation: an Operations Research (OR) Approach.

"Global Air Traffic Management' has to make a transition from the localized to the global view of the ATC system, by analyzing the logic and the coordination of system functions that have to be automated whenever possible.

To accomplish this task it is necessary to use a modeling abstraction that strips ATC from its particular characteristics down to its functional essence, the "Dynamic Space - Time Resource Allocation System".

3.4.1 The Resource

A flight is but as a sequence of way-point appointments from gate x of airport A to gate y of airport B. If two appointments coincide, we have a collision or a near miss.

The straight forward discretization of the space-time continuum, required for explicit airspace booking, has thus the form of a network of "space-time slots". This network models the resource to be dynamically allocated to flights, through a Command, Control and Communications structure.

Such an approach simplifies matters, as opposed to the Control Volume Approach which poses unnecessarily complex, though mathematically challenging, airspace geometry problems. It also overcomes a basic handicap in quantifying the notion of Airspace Capacity.

The first level of aggregation of this network results in a set of airport super nodes, traffic sources and sinks, connected via the En-Route network of way-points.

The airport

The airport abstraction is that of a queueing system whereby runway service is provided to arriving and departing flights. Efficiency of this service is achieved through optimal runway scheduling that exploits early flight plan information.

The runway scheduling activity is the system's bottleneck and the place where, traditionally, airspace reservation begins. Runway scheduling is mainly concerned with maximizing the runway throughput, or runway capacity, subject to airport parking limitations that may cause the "Gate Locking" phenomenon.

Maximizing runway capacity is crucial to system performance in terms of fuel economy, delay reduction and safety. It is also a complex issue, since runway capacity depends on random quantities such as traffic mix and sequence and weather conditions.

Flow Management

GATM has to further consider the coordination of runway scheduling activities among airports whereby, knowing the time of a flight's landing appointment, a flight spends its delay on the ground rather than wasting fuel and contributing to the destination terminal area congestion.

In view of the stochastic (random) nature of the airport capacities, the large number of airports and the ever increasing traffic volumes, this global coordination function, known as Flow Management, is complex and delicate.

So far it has performed in a crude manual way, by metering strategies that regulate the "control volume" (sector or ATC center) influx of traffic. However, modern TELEMATICS open the way for personalized Flow Management that is efficient and fair to the users.

3.5 Dynamic Programming, Stochastic Optimization and Complexity

Typically, the solution to stochastic optimization problems works its way backwards from the anticipated future. This is true of flow management, where each flight has to weigh its departure time based on its confirmed landing slot, whose materialization time is a random variable.

Whether explicitly or implicitly, the solution has to evaluate, in an organized fashion, all possible outcomes in order be able to induce the best at decision time. This is a game against nature where the term "nature" is defined to include apart from the weather the uncontrolled behavior of the ATC players. After nature's move we have to update our plan, moving down on some path of an immense decision tree.

Decision trees grow rapidly in size and therefore one has to employ tricks exploiting the special problem structure in order to arrive at solutions that would be feasible in terms of computational resources and expedient for real time application.

One practical way of dealing with such problems is the use of rules, which are based on experience, intuition or even partial modeling. Although rules do not guarantee optimal solutions, they are not ruled out as an option for flow management by virtue of their expediency.

There is also a possibility that they may lead to an optimal solution. Consider for instance the Market Model for the Space Time resource, presented below (sect. 5, pp. 14-5), and the explanation on how a market arrives at an equilibrium. One may be able to seek optimal flow management by defining the rules for the digital stock-brokers.

Another analogy is that of to finding a system's equilibrium solution through the principle of energy minimization. The usual example of this principle is that of determining the shape of a hanging chain. Perhaps the rules in our system might imitate the behavior of the chain links under gravity.

3.6 OBJECTIVE: Maximum User Autonomy

"... When aircraft first became available there was but a FULLY AUTONOMOUS SYSTEM where aircraft flew as they wished. As traffic grew denser, pilots had to place their trust with an external body, the ATC establishment, that having as complete as possible a picture of the traffic, could guide them safely to their destinations, thus, returning their AUTONOMY in a safe way ..."

Centralizing the information about everyone's position and direction, enables the system to allot safe airspace to the flights. Contrary to trends that view it as a system design variable, user autonomy, the freedom of flights to pursue leisure and commercial objectives, is a system objective. Maximizing user autonomy requires:

1. Maximization of the Safe Airspace Capacity: the "space-time resource"
2. Alternative Mechanisms: for users to share this resource, for example by auction or fixed prices
3. Tolerance: for the spectrum of needs, equipment and even cultural trends across nations
4. a System Description Language: general enough, to describe individual user characteristics as long as they conform to a minimum standard that facilitates communication.

In terms of the OR methodology, an objective is quantified by expressing it as a weighted function of its constituents. This function may often be a simple summation. It may also, however, be difficult to establish a quantified relationship between constituent objectives, in which case one may resort to a decomposition of a complex problem. For example, whereas in principle one might be able to cast GATM as a huge optimization problem, in practice we decompose it in three components: route structure, runway scheduling and flow management, each having its own objective as will be discussed below.

4. NETWORK REPRESENTATION OF THE SPACE-TIME RESOURCE:

Figure 1 illustrates schematically the principle of space-time discretization, showing permissible transitions (arcs) between slots on spatially neighboring waypoints (A and B). The rule of determining the permissible transitions depends on the aircraft speed and prevailing wind conditions, which implies that the slot structure has to be constructed dynamically on the fly. This network discretization facilitates the logistics of the GATM process such as:

- Traffic book-keeping, where flight progress information is handed over automatically through the network
- Optimal dynamic routing, i.e. finding non intersecting 4-D tubes around obstacles, bad weather and areas that are congested or reserved by the military. Removing slots along a path assures no conflicts with paths to be computed.
- Mapping of hierarchical command & control structures, such as national authorities, by partitioning the global node set.

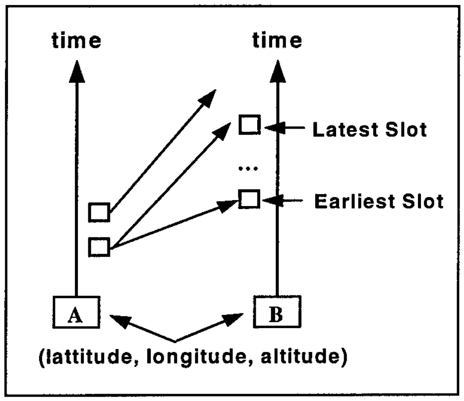


Figure 1: Schematic transitions in the Space-time network

Modern TELEMATICS enable the fine grain resolution of the network representation which allows for quantification of the notions of airspace capacity, level of safety, performance criteria and complexity. Furthermore, network representation allows the establishing of indices that guide the choice of strategic options which affect the deployment of GATM.

OR graph theory, for example, provides a maximum flow theorem that could be suitably manipulated to yield a quantification of airspace capacity that respects traffic directionality. One may further use traffic equilibrium algorithms to assess the efficiency of a given network structure for a variety of scenarios, establishing macroscopic indices.

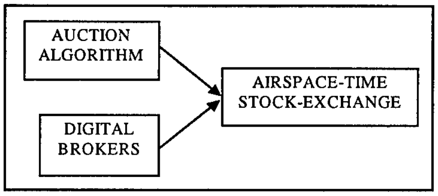
Level of safety may be also quantified by expressing it as a function of system parameters such as the waypoint slot size and the logic of the path finding process.

One may view level of safety as a very special system performance index. Similarly, one may construct indices for performance criteria relating to passenger delays, fuel cost and pollution that will be linked to system parameters as well as to the choice of logic (algorithm) and level of system automation.

GATM is a chaotically complex subject and our approach is to impart it with rationality that would allow us to deal with it effectively. Although an implemented GATM is going to be further complicated by the selection of physical equipment, personnel and training, at this point we are concerned with its functional complexity. For instance, tactical, real time GATM aspects, require timely solutions of optimization problems and one may often have to compromise optimality for timeliness.

OR and the Network Representation allow GATM to borrow mature routing, scheduling etc. techniques and methodologies from other large scale resource allocation problems encountered in military logistics, scheduling, routing and computer science.

Notice, that in designing a GATM, one should be able to experiment by changing either or both the network structure and management logic and this brings out the importance of a user-friendly flexible simulation.



5. A FREE MARKET SCENARIO OF THE ATC/ATM SYSTEM:

Question: can air traffic be as autonomous as highway traffic?

Answer: Not if the pilot has to coordinate with other traffic!

Whereas there are Airborne Collision Avoidance Systems that allow for pilots to sense the traffic around them, the amount of data and size of equipment required for on-board decision making render such an idea impractical if not impossible.

The Digital Airspace-Time Stock Exchange

The digital stock market scenario was inspired from the Auction Algorithm, implemented by the author within Space Based Battle Management R&D. Further experimentation using computer simulation, whereby behavioral models of flights:

1. simulate aircraft dynamics,
2. communicate with models of ATC,
3. negotiate flight-plans,
4. occasionally disobey ATC instructions, i.e. they are capable of erratic behavior,

and ideas from object oriented modeling, facilitated by computer languages such as LISP and C++, make the free market scenario just the natural next idea.

The Auction Algorithm: is mathematically interpreted as a coordinate descent method that finds the minimum of convex objective function. It bears, however, an intuitive analogy with the market bidding process, where a global price / demand equilibrium is sought.

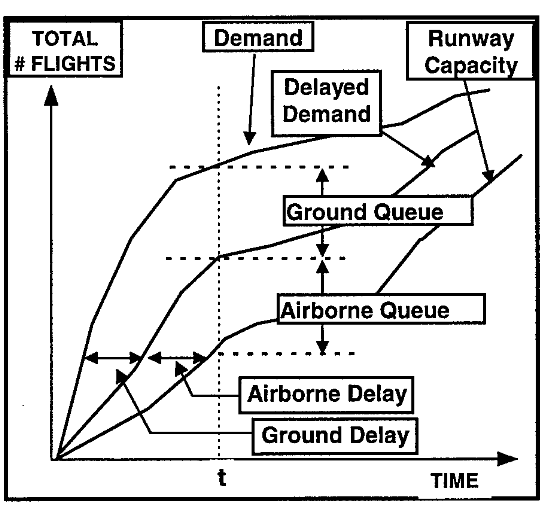


Figure 2: Schematic of The Flow Management

The notion of price, may only be virtual, used as an indication to the individual of how much the rest of the community values a certain "slice of the resource". Typically, prices are raised during the auction resulting in a shift of bidder's choice until everyone has the slice he can afford.

It has been shown that this auction mechanism leads indeed to a global optimum. Moreover, it is parallelizable in that every bidder can calculate his bids independent of the others, and this feature made it a candidate for the "weapon to target assignment problem" for battle management whose solution is time critical.

Also, the prices impart a memory to the solution, which is very important in time critical situations since upon arrival of new bidders, the solution continues from where it left off; it does not have to start all over again. Parallelicity and solution memory brought an order of magnitude improvement to the "weapon to target assignment problem".

Digital Brokers: in our days, where computer trading is commonplace they should not sound as science fiction. They are smart images of flights, i.e. parametric expert systems residing on high bandwidth network of connected ground computers which will undertake a dual task composed of:

1. regular ATC function: i.e. flight tracking (filtering surveillance data), flight-plan conformance and vectoring when necessary
2. commercial function: i.e. bidding for the space-time resource that may take the form of priority negotiation.

To give an example, consider two flights that have been allocated a landing slot, contending over the same slot of a common way-point. The price each flight is willing to pay for the way-point slot depends on its ability to take a small delay. For example, on a long journey such delay can be made up with speed control.

6. ESSENTIAL SYSTEM FUNCTIONS

6.1 FLOW MANAGEMENT:

Figure 2, illustrating the flow management problem, corresponds to a typical runway "busy period". The top "Demand" curve counts the number of flights that wanted to use the airport at time t. The bottom curve, "Runway Capacity", counts the number of flights that may have operated at time t, given the runway configuration, minimum ATC horizontal separations and prevailing weather conditions.

The middle "Delayed Demand" curve is the product of Flow Management and counts at time t, the number of flights that wait at the vicinity of the airport.

The interpretation of the vertical distance between the lower two curves counts the number of aircraft that wait airborne in the airport terminal area (TMA) whereas the vertical distance between the upper two curves is the "airborne queue" which is distributed all the way to each flight's departure airport.

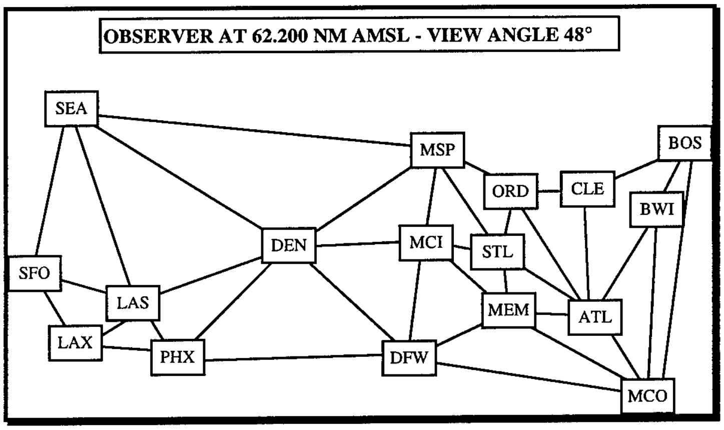


Figure 3: TMSIM showing major US airports

The horizontal distances between the curves, as shown on Figure 2, measure "ground/airborne" delay portions suffered by the flight that landed at time t.

Notice also on Figure 2, that the area between the lower two curves is a measure of wasted fuel, where as the traffic density, and hence collision hazard in the TMA, is directly proportional to the size of the airborne queue.

In a predictable world, where capacity would be *a priori* determined, the middle curve would coincide with the capacity curve. Given, however, the uncertainty in the capacity curve, a positive airborne queue ensures that the runways remain busy during a busy period.

A simplified but instructive version of the flow management problem is as follows. Consider that the arrival airport has two time buckets x and y. Bucket x has a random capacity with a known probability distribution, whereas bucket y has infinite capacity. If a flight opts for y it incurs a unit ground delay with cost d_g, whereas if it opts for x, it incurs a unit of airborne delay d_a, with probability p, i.e. that bucket x will be full. The choice hangs in the balance between ground cost d_g and expected airborne cost $p \times d_a$.

En-route conflict resolution complicates flow management even further contributing uncertainty about trip length.

Flow control Strategies
To our knowledge, there is no known algorithm that solves optimally the flow management problem. There are, however, strategies that combine in an "ad hoc" or "heuristic" way optimal solutions to sub-problems.

The author has experimented with two types of flow management strategies using his simulation facility that works as follows. At first, the simulation reads the flight-plans in the order of submission time (time-stamp). For each flight-plan a flight object is created that requests a take-off slot at the airport of departure. Based on an estimate of travel time, it requests a landing slot at the arrival airport. If the landing delay is anticipated to be larger than a number x of minutes, then the flight has to decide on how to spend its delay.

The first strategy is a simple one whereby the flight chooses to postpone take-off, allowing itself some slack time for unexpected en-route conflicts and bad weather. As the flight approaches its destination airport the remaining slack time is absorbed by speed reduction and delay manoeuvers. A brute force way of estimating a reasonable slack time is simply by trial and error over a number of simulation runs.

The second strategy introduces the notions of airspace-time auctioning and priority negotiation discussed above. This topic deserves special attention and the author has submitted a proposal for its study, by the acronym ICAROS (Intelligent Concepts in Airspace-Time Resource Sharing, June/94) in response to the a call for tender from the European Commission's DG VII "Exploratory Actions In RTD In Air Transport"

6.2 ROUTE NETWORK STRUCTURE:

Ideally the route structure should provide great circle (GC) paths at least between major international airports. However, whereas direct point-to-point navigation is today possible (RNAV) in areas where traffic is dense, one needs to consider the network airspace structure discussed earlier.

If direct GC paths were allowed, the number of possible intersections increases geometrically with the number of airport-pairs. One might therefore try to lump neighboring intersections together in order to control node density. Higher density implies more alternative equivalent paths for each airport pair and hence higher airspace capacity at the expense of complexity.

The author has experimented with a recursive algorithm for generating a route structure with controlled density that utilizes major navaids to mark way points when possible. The algorithm shown below, loops over the airport pairs using procedure SPLIT to recursively search for intersections with existing arcs.

```
For each airport-pair (A&B) SPLIT(AB);

Procedure SPLIT(AB) {
  draw the GC arc AB;
  for each of the existing arcs x {
    if x intersects AB at P{
      if (there is a navaid or defined way-point
          within radius R )    /* density control */
           then set P to that point;
    }
    SPLIT(A,P);
    SPLIT(P,B);
    }
}
```

The travel distance on the shortest path is of course longer than the GC arc, and it is possible to derive an analytical expression linking the increase in length with node density. The author is planning to publish in due time a paper explaining the method and results. Notice that efficiency of the space-time network design hangs in the balance of node density and traffic density and directionality.

6.3 TRAFFIC EQUILIBRIUM

When traffic jams occur in a city, drivers tend to divert, often exploiting narrow streets, in order to avoid them. This practice leads to a traffic equilibrium, where the system reaches a steady state with relatively stable flows on all the streets.

This idea carries over to the airspace route network as well, and we propose to use it for macroscopic assessment of node density.

For this purpose the author used an "All Shortest Path Algorithm (ASPA) With Node Capacities & Penalties". This algorithm arrives at an equilibrium traffic distribution, if such a distribution exists for the given node and traffic densities iterating over the list of airport pairs.

At first, ASPA assumes a function that relates node penalty, (i.e. average time delay for crossing it), to the total traffic that is registered with the node as well as to the node capacity. Then for every airport pair the shortest-time path is found and the average daily traffic (averaged over summer season for example) is added to all the nodes (way-points) on that path, contributing to the node penalties.

Notice that when the first airport pair x_1 was considered, node penalties were zero. If at the end of the first iteration over the airport pair list we subtract the traffic load of x_1, this has only a marginal effect on the accumulated node penalties. Finding a path again will result in a new node sequence.

It was observed in several trials that the iteration of removing and re-finding paths converges after only a few passes of the airport-pair list. These experiments were carried out with TMSIM, using traffic volumes between major US airport hubs as shown on Figure 3, supplied by the Transportation Systems Center, US DoT, Boston Massachusetts.

6.4 RUNWAY SCHEDULING AND CAPACITY PREDICTION

6.4.1 The Algorithm

It has been observed that grouping of similar aircraft in the landing sequence accelerates the rate of runway operations. This property, which is a result of wake vortex considerations, is extremely desirable, when airports operate near saturation, because, according to queueing theory, delays are sensitive to the rate of operations.

The author's doctoral dissertation dealt with the subject producing an Optimal Runway Scheduling Algorithm (ORSA). ORSA takes as inputs the minimum safe horizontal ATC separations, aircraft approach speeds and weights, as well as runway coordinates in order to produce dynamic runway scheduling.

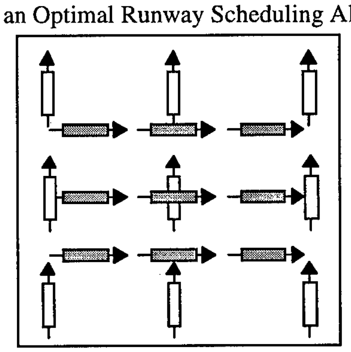


Figure 4: Runway Crossing Relations

In a preprocessing step ORSA analyses the pair-wise runway relationships for parallel and crossing runways. Figure 4 shows the 9 possible runway crossing possibilities. For each possibility, the distance to the runway crossing point is calculated, which given aircraft speed, translates into the times from each runway threshold to the crossing point. Taking the maxima of such times over take-off and final approach speeds for each aircraft weight class we construct a matrix of minimum safe time separations for every runway and flight pairs.

Then ORSA looks at the ordering of flights according to the First Come First Served (FCFS) discipline and searches all possible rearrangements to find the one that minimizes a total delay function subject to the Maximum Position Shift (MPS) constraints.

The MPS constraints have been introduced in order to avoid the unfair possibility where a flight is indefinitely displaced backwards in the queue. An MPS value of zero, forces the choice of the FCFS sequence.

As will be verified from the results shown below, a modest MPS value of 2 or 3 can make substantial improvements of the order of 20% to the runway capacity.

Whereas people usually resent losing their place in the queue, ORSA' s impartial treatment of flights promises a zero shift on the average, to ease pilot psychology, and less delay despite a backward displacement due to increased efficiency.

An important technical feature of ORSA lies in its foundation on Dynamic Programming techniques, where by the solution space is coded and de-coupled, so that it may be searched in parallel. This has been achieved by careful exploitation of the structure imposed by the MPS constraints. As a result, ORSA is computationally efficient and requires solution time directly proportional to the number of flights considered for scheduling.

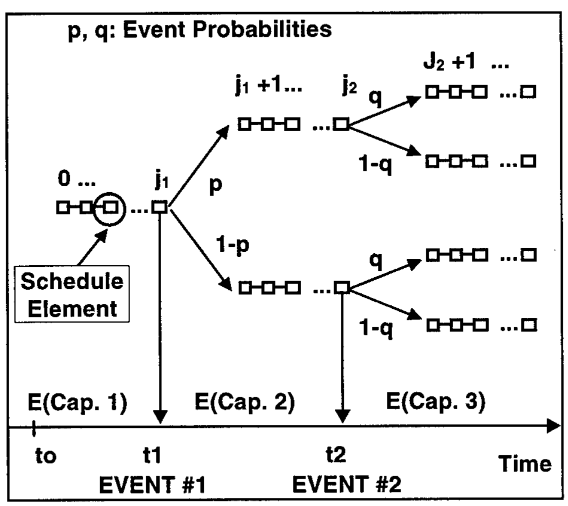


Figure 5: Runway Capacity Prediction: the "Schedule Tree

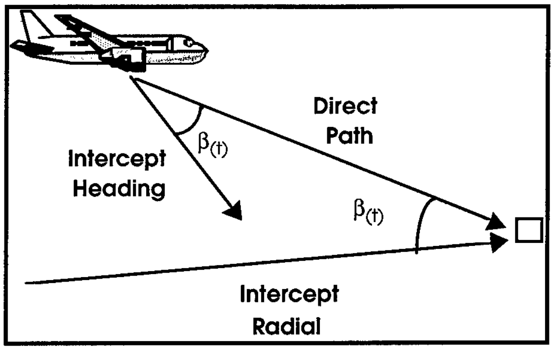


Figure 6: TMSIM' s simplified aircraft model

This compares favorably with scheduling that relies on heuristic Branch and Bound techniques and whose worst case solution time requirements grow exponentially with the number of flights, and do not therefore guarantee a timely optimal solution.

6.4.2 Prediction

Figure 5 shows a possible use of a fast runway scheduling algorithm for runway capacity prediction through the compilation of the schedule tree.

The schedule tree allows the exploitation of *a priori* probabilities about possible changes in runway configuration, producing accurate worst case as well as average capacity predictions.

Suppose for instance that at time t_1 a front is expected to pass north of the airport with probability p or south with probability 1-p. By bifurcating the schedule at t_1 we able to compute an average capacity beyond t_1. Similarly, we can have additional bifurcation at t_2 etc.

Notice, that the capacity figures produced with this method are not figures of merit that come out of a statistical formula, where actual capacity may fall below the anticipated; they are guaranteed since we have the schedules that generate them.

7. TMSIM: A GLOBAL TRAFFIC MANAGEMENT SIMULATION

7.1 Description

TMSIM is a comprehensive, object-oriented simulation tool that allows one to build an understanding of the structure and functionality of the Air Traffic Control System, by modeling its components and their interactions.

It has been developed by the author at the Massachusetts Institute of Technology (MIT) and at the Transportation Systems Center (TSC), US Department of Transportation, in order to evaluate Air Traffic Management strategies. TMSIM provides the necessary environment for evaluating runway capacity by measuring the number of operations per unit of time in a realistic context, which includes:

1. exact route network representation for the En-route as well as the Terminal Area, that can be interactively modified using the mouse

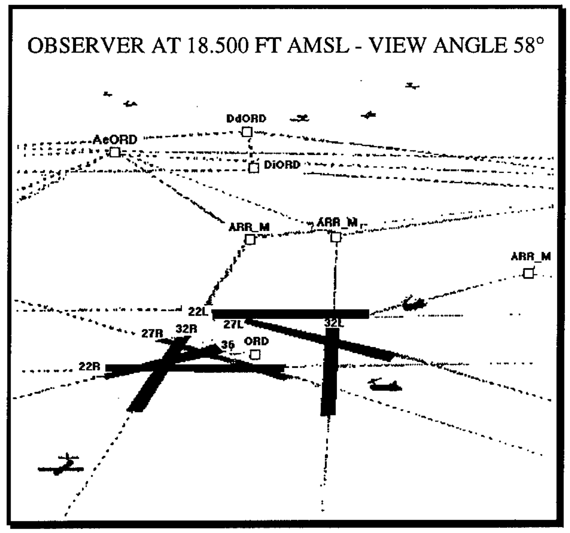


Figure 7: TMSIM: 3-D view of the Chicago O' Hare virtual airport

2. autonomous flight (see Figure 6)and ATC objects, that can communicate with each other
3. ability to read a traffic sample, in the form of a file containing flight plans, or generate random traffic sample with a specified composition
4. dynamic flight planning, routing, scheduling, and communications processes that may take into account conflict detection and resolution
5. 3D animation (Figure 7) that allows the user / observer to trace a flight all the way from take-off to landing and verify that separation standards are maintained
6. interrogation of flight, route network and ATC objects using the mouse and pull-down menus
7. advanced algorithms for scheduling, shortest path routing, flow management, airspace restructuring (sectorization), and capacity and workload analysis.

TMSIM enables the evaluation of strategic options concerning, for instance, airspace structure in both holistic and incremental "what if we add an extra runway" fashion. It further enables the macroscopic evaluation of micro-level behavior of flights and tactical ATC.

8. RUNWAY SCHEDULING RESULTS

TMSIM features allow upstream events to influence the rate of runway operations, thus presenting an accurate picture of the "materialized" airport's capacity. In other words, the results presented are not merely the product of a one time run of the scheduling algorithm; they are the actual, recorded landing and take-off times, as they were shaped by the entire dynamic ATC/ATM process.

8.1 Frankfurt EDDF

8.1.1 En-Route & Airport Configuration

The Frankfurt (EDDF) TMA is one of the busiest in Europe currently managed by the COMPASS system. There are two close-parallel runways (25L &25R) available for landings and takeoffs. A third runway

(18/36) almost at right angles, is available for takeoffs only. Conservative minimum runway separations were chosen in order to simulate full Instrument Flight Rule (IFR) conditions.

In order to limit the scale of this exercise, secondary airport traffic was assigned to 162 major airports, in Europe, Africa and Asia.

The route structure connecting airports has been automatically generated using TMSIM' s network generation procedure (section 6.2). Route segments longer than 500 NM, were broken up in smaller ones along the great circle joining the corresponding origin destination pair.

8.1.2 The Traffic Sample

The traffic sample is representative of a busy summer day (July 6,1990) with the following composition:

- Total 714 Flights: 49% Landings, 51% Take-offs
- 12% Light, 75% Medium, 13% Heavy

8.1.3 Time scaling

Time scaling is a simple technique that produces a denser traffic scenario, by compressing the time axis, without disturbing the traffic orientation and composition. A time scaling factor of 0.65 was used in order to:

1. compensate for local and intercontinental traffic that was missing from the traffic sample
2. create an artificial overload situation in order to obtain an extended runway busy period.
3. Notice on Figure 8 that as a result of time scaling the demand tapers off at time t=16, as opposed to t=24.

8.1.4 Demand & Capacity Results

Figure 8 introduces the temporal distribution of the rate of demand for runway use, and the runway capacity response with First Come First Served (FCFS) scheduling (i.e. zero Maximum Position Shift (MPS).

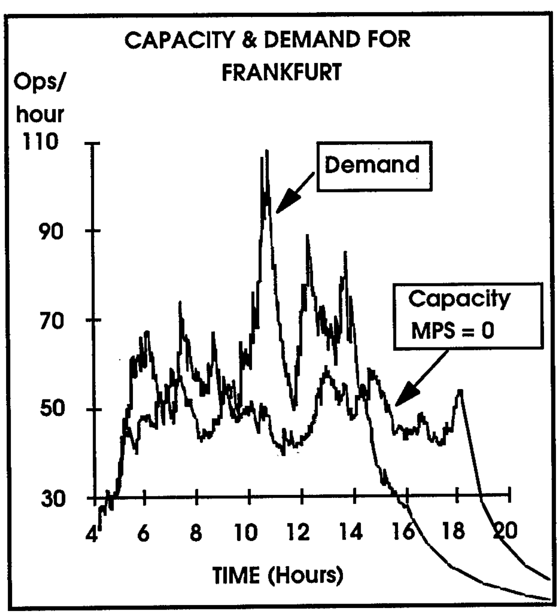


Figure 8: Demand and Capacity with MPS=0

Notice that the demand rate is maintained higher than the capacity rate until about t=15, when demand diminishes, whereas, the capacity continues at a high level until approx. t=18, in order to absorb the delayed traffic. This is due to the fact that Flow conservation requires that the areas under the demand and capacity curves should be equal.

8.1.5 Temporal Comparisons, MPS = 0, 1, 2, 3

Figure 9 shows how optimal scheduling raises the temporal capacity curves. For clarity of presentation, low demand times have been trimmed off.

As expected a higher MPS value results in a "sustained higher scheduling performance". Also, consistent with the flow conservation argument, the higher MPS curves drop off sooner as they absorb the demand faster.

8.1.6 Mean Value Comparisons & Delay Improvements

Figure 10 shows the mean capacities achieved for MPS values of 0, 1, 2 and 3. The average is taken from the temporal capacity curves over the busy periods, i.e. when there is a positive queue of flights waiting for their turn on the runway. The computed respective improvements of:

12%, 18% & 22%

over the MPS=0 case are significant, because they dramatically reduce delay by

53%, 60% & 70%

respectively, as shown on Figure 11. This result is perfectly consistent with the queueing theory stating that as the customer arrival rate λ approaches the service rate μ, the delay in the queue tends to infinity as

$$1/(1-\lambda/\mu)$$

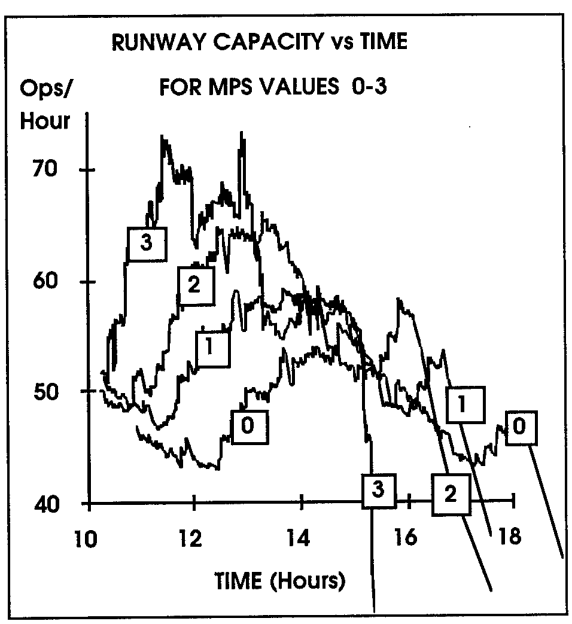


Figure 9: Temporal Capacity comparisons for MPS values of 0, 1, 2, and 3

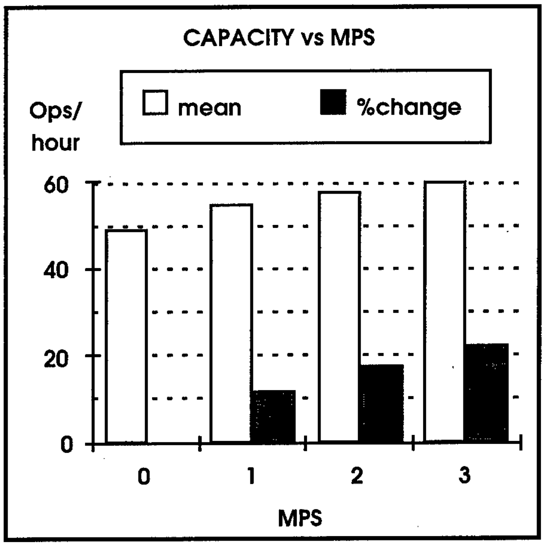


Figure 10: Mean Capacity comparisons

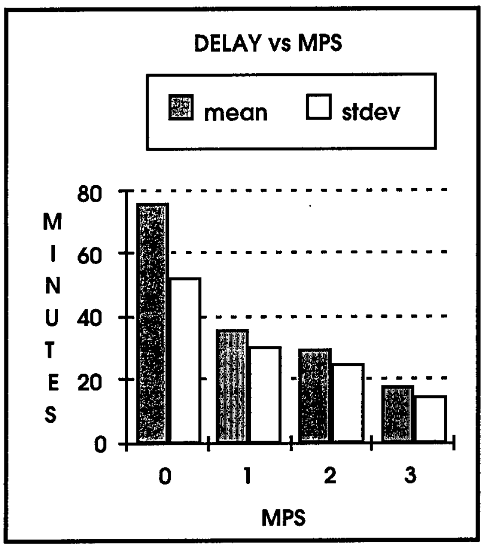


Figure 11: Mean Delay comparisons

8.1.7 Runway Capacity versus Traffic Mix

It has been stipulated in the past by a variety of ATC experts that the runway capacity improves as the traffic mix becomes more balanced. The large final approach separations required for consecutive landings on the same runway, makes it profitable to insert take-offs between them on the same or on a crossing runway. Figure 12 verifies this stipulation. In particular, the following observations and comments can be made:

1. Runway capacity as a function of take-off content, for MPS values 1, 2 & 3, is an imperfectly symmetric bell-shaped curve maximized at 50% take-offs.
2. The curves are better defined in the centre. This is because an almost balanced traffic mix prevails in steady-state and therefore more data are available in this region.
3. The optimization seems to be more effective when the traffic mix is balanced. At 50% take-offs the runway capacity jumps from 60 to 80 ops/hour as MPS changes from 1 to 3; an improvement of 33%.

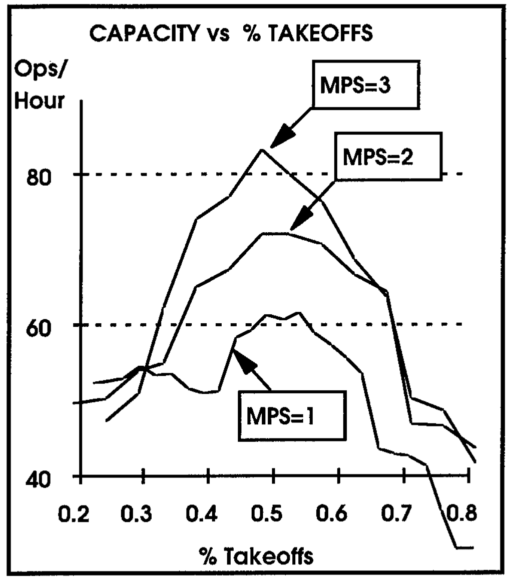


Figure 12: Capacity versus percent Takeoffs

The last observation stresses the importance of optimal runway scheduling, because it implies that the bigger gains are materialized during the normal operating conditions.

8.2 Chicago O' Hare (ORD)

8.2.1 TMA Configuration

This section presents the runway capacity results for Chicago O'Hare (ORD), the busiest US airport, for MPS values 0 and 2. Figure 7 shows a westerly runway configuration with seven active runways. In order to limit computational requirements, traffic from secondary airports has been assigned to the 26 major (pacing) airports. The actual runway systems have been supplied for each of these airports.

8.2.2 The Traffic Sample

The traffic sample contains approximately 1870 fligh-plans filled on March 1, 1989, between Chicago O'Hare and other US airports. It is composed of 3% Light, 95% Medium and 2% Heavy aircraft. In order to limit the computational effort, secondary airport traffic has been assigned to the closest major (pacing) airports.

The traffic composition is biased in favor of medium sized aircraft due to the absence of local and international traffic in the database. The demand was artificially inflated by scaling the time axis with a factor of 0.7.

8.2.3 Capacity Comparisons MPS=0 & 2

On Figure 13, showing the cumulative curves for the runway demand and capacity, we observe that the optimal cumulative capacity curve with MPS=2 is markedly superior to the one for MPS=0. Comparing the areas between the capacity and demand curves, it may be verified that the delay suffered with MPS=2 is about a tenth of that suffered with MPS=0.

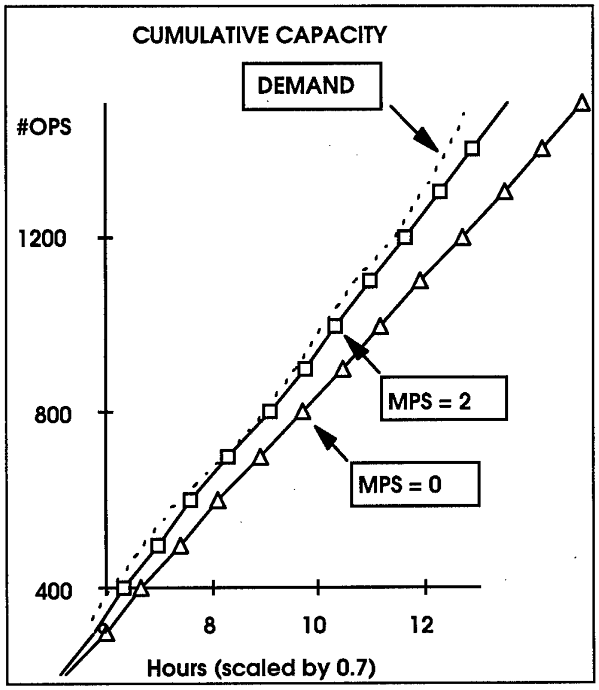


Figure 13: Cumulative Demand & Capacity, MPS=0, 2

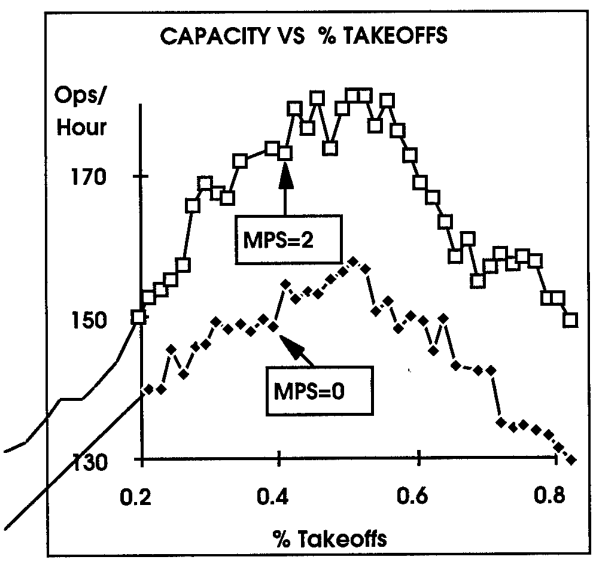


Figure 14: Capacity vs. Percent Takeoffs, MPS=0,2

The computed mean capacities jump from 133 flights / hour with MPS=0, to 154 flights/hour with MPS=2, with peaks exceeding 180, a 15.8% improvement. This is consistent with the results concerning the Frankfurt airport.

The computational load for runway scheduling grows with the square of the number of runways and exponentially with the value of MPS. Therefore, due to equipment limitations, the capacity evaluation with MPS=3 was not performed. However, a 20% improvement would be a reasonable extrapolation.

8.2.4 Capacity vs %Take-offs, MPS = 0 & 2

Figure 14: Capacity vs. Percent Takeoffs, MPS=0,2 presents the runway capacity as a function of the takeoff content (%Takeoffs) of the traffic mix. As was the case with Frankfurt, but with a larger traffic sample and more complex runway structure, it is observed that:

1. The runway capacity curve reaches its maximum at 50% take-offs.
2. The MPS=2 curve is consistently superior to the MPS=0 curve, the respective maxima being approximately 180 and 150 operations/hour.

The optimization is more effective when traffic mix is well balanced.

9. CONCLUSION

Within the confines of this paper it was only possible to present an overview discussion of the main issues involved in GATM, each of which is a research topic in itself.

We note in conclusion that preliminary results from runway scheduling are encouraging. TMSIM, which so far is really only a specification, shows that the much needed experimentation with GATM concepts does not have to be expensive, or unnecessarily sophisticated.

GATM needs to be opened up to the community for solicitation of ideas and cross-faculty exchange which will promote creativity. Ideas such as the free market scenario may not really be far fetched science fiction.

Finally, we note that the concepts presented will require minimal changes in terms of physical equipment and personnel. Traffic controllers may continue, at least for a while, their job as they know it, keeping a monitoring window on the system. Only that traffic will be magically resolved relieving their occupational stress.

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Optimal Scheduling with Maximum Position Shift (MPS) Constraints: A Runway Scheduling Application

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Abstract

The airport's runway system may be viewed as a queueing system where a stream of flights is waiting to receive take-off or landing "service". It has been observed that changing the order of runway operations results in a different runway throughput or "capacity". This is due to wake vortex considerations, whereby the minimum horizontal separations between successive landing aircraft depends on their weight and final approach speed.

This observation gave rise to the Optimal Runway Scheduling Problem (RSP) that seeks to find the optimal rearrangement of flights that would maximize runway throughput. RSP is complicated by the fact that in a real time system, where flights appear randomly over time, there is always a possibility of some flight being indefinitely displaced backwards in the queue. This calls for the Maximum Position Shift (MPS) constraints which assure that no flight will be displaced in the queue by more than a pre-specified number k of positions. The term queue refers to the ordering of flights according to the First Come First Served (FCFS) discipline.

The RSP is typical of queueing systems when service rate depends on customer ordering. It is also a variation of the notorious Traveling Salesman Problem (TSP). The paper presents the Parallel Dynamic Programming RSP algorithm, developed in Trivizas' doctoral dissertation. Timely solution is crucial to real time dynamic scheduling, and so the paper concentrates on its computational aspects. It is shown that the MPS constraints reduce the size of the problem's solution space, interpreted as a computational neighborhood around the FCFS sequence of "radius" equal to the MPS value. This neighborhood has the form of a permutation tree (PT).

It is shown here that traversing the PT using a Branch and Bound (BB) Depth First Search, a brute force method, may require an amount of time which is exponential in the number n of customers (flights).

It is further shown that the search may be organized efficiently using Breadth First Search Dynamic Programming which exploits the de-coupled, stage invariant solution space structure, whose size, $2^{MPS} \times n$, is linear in n and exponential only in the bounded value of MPS.

Stage invariance and label vector coding of the solution space allow for a generalized cross-section of the solution space; this leads to the concept of a parallel computation engine that sweeps the solution space in time linear in n.

1. INTRODUCTION

The paper presents results from Trivizas' doctoral dissertation ([12]), on the problem of Scheduling with Maximum Position Shift (MPS) constraints. The problem typically arises in a queueing system, when the service rate depends on the sequence in which customers are handled by the server. Such a queueing system is the airport runway system, where it has been shown ([3], [10], [12]) that rearranging the sequence of landings and take-offs affects the runway capacity, i.e. the rate of runway operations. An optimal Dynamic Programming (DP) scheduling algorithm is developed that takes as input the set of currently known flights, their desired time of operation, basis of the First Come First Served (FCFS) sequence, and a matrix of Air Traffic Control (ATC) minimum time separations, in order to produce an optimal schedule defined as runway and threshold time assignments maximizing runway capacity.

The Runway Scheduling Problem (RSP) has received a lot of attention over the last two decades from the FAA and research institutions. RSP is important, because even small improvements in capacity, of the order of 5%, are critical for the safety and fuel economy at times of congestion, when a minute system delay translates to thousands of passenger minutes. It has been found ([3],[10],[12]) that optimal scheduling may increase capacity up to 20%. A good runway schedule provides air traffic controllers a near term plan that helps assign flights conflict free space-time paths in the airport terminal area. Moreover, a fast RSP solution may be used for airport capacity assessment in a global traffic management system.

In an ATC environment the schedule changes dynamically in order to accommodate new flights wanting to use the runways. Therefore, solution speed is crucial to its real time application and this paper concentrates on the computational aspects of RSP.

Computationally, RSP is a variation of the notorious for its complexity Traveling Salesman (TSP) problem, where a salesman seeks to find the shortest route visiting once a number of cities. This is because the minimum safe time separation (distance) between successive flights (cities) depends on their type, in our case characterized by the final approach speed and aircraft weight.

RSP is characterized by the Maximum Position Shift (MPS) constraints which limit the backward shift of a flight in the queue, so as to avoid the possibility of any flight being indefinitely postponed upon new arrivals.

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

In complexity theory, TSP belongs to the class of "Non-deterministic Polynomial (NP) complete" problems for which no exact polynomial algorithms are known to solve them. Solving optimally a TSP with n cities requires an amount of computation proportional to 2^n, prohibitive for real time applications. Fortunately, the MPS constraints reduce the computation effort drastically, to a linear function of the number n of flights.

The paper develops the concept of the Permutation Tree (PT), the finest grain representation of the problem's solution space, comparing the two major approaches for searching for the optimal permutation: the Branch and Bound (BB) Depth First Search (DFS), and the Dynamic Programming (DP) Breadth First Search (BFS).

Despite the considerable pruning of the solution space by the MPS constraints, BB-DFS is a brut force method that repeats computations. It is shown here to sustain the prohibitive exponential worst case performance. The DP approach, however, exploits the MPS structure reducing drastically the computation effort to a linear function of n, with a constant of proportionality of 2^{MPS}. This is achieved through a systematic breadth first search of the solution space, in an incremental shortest path fashion., using a sophisticated coding.

The solution space is shown to have a stage invariant structure, which collapses into a generalized cross-section. This cross-section is the backbone of the "Parallel MPS Sequencer", a parallel computation engine, that sweeps through the solution space with up to 2^{MPS} CPUs in lock step, in order to produce the optimal MPS feasible schedule in time linear to the number of flights.

The paper starts with definitions of the RSP, elaborating on the objective function, a mathematical expression of delay cost, examining its form and special features. These features derive from the generalization of RSP that allows mixing takeoff and landings as well as operations on a system of interacting runways.

In both cases, the extended RSP cost matrix, containing the minimum safe time separations between successive operations on the same airport runway system, violates the triangular inequality, because it is usually possible to insert one or more takeoffs between successive landings on the same runway without stretching their separation. Similarly, one may be able to insert operations on a crossing runway. The paper shows how these features are accommodated by the parallel sequencer, which takes further account of the distance each flight has to travel within the airport terminal area, in its flight to runway assignments.

2. The Runway Scheduling Problem (RSP)

Runway scheduling has three mathematical models of increasing complexity: RSP1 allows only landings or only takeoffs on a single runway, RSP2 allows mixed takeoffs and landings on a single runway and RSP3 allows multiple runways. Each of these problems can be extended to its dynamic or real time version.

2.1 Definition of RSP1

In abstract terms, the runway scheduling problem can be stated as follows:

Given:

a) a set $S = \{i: 1 \le i \le n\}$ representing flights indices in the FCFS discipline

b) a set $P = \{i: 1 \le i \le n\}$ representing positions (or slots) in the queue

c) a set of Maximum Position Shift Constraints:

$$|i-j| \le MPS, \; i \in S, \; j \in P \tag{1}$$

d) a cost matrix containing safe minimum time separations between consecutive flights on the same runway.

$$c_{ij}, \quad i,j \in S \tag{2}$$

find a MPS feasible permutation:

$$\pi_{(S,\,MPS)} = \left(i_1 \; i_2 \cdots i_j \cdots i_n\right) \quad \text{where } i_j \ne i_k \;\; i_j, i_k \in S \;\; j,k \in P \tag{3}$$

That minimizes:

$$z\left(\pi_{(S,\,MPS)}\right) \tag{4}$$

Due to wake vortex considerations, whereby lighter aircraft stay further behind heavier ones, than the opposite, differences in speed and weight among aircraft make the cost matrix asymmetric. As a result, the time required to operate a set of aircraft, and therefore runway capacity, defined as rate of operations, depends on the traffic mix and sequence.

The simplest cost function, equivalent to the length of a TSP tour, is the total time to operate the set of aircraft, or Time of the Last Operation (TLO), given by:

$$TLO = z\left(\pi_{(S,MPS)}\right) = \sum_{\substack{0 \le k < n \\ i_k \in \pi_{(S,MPS)}}} c_{i_k, i_{k+1}} \tag{5}$$

where i_0 is the flight that has just operated.

Total Weighted Delay (TWD) is another cost function defined as the weighted sum of individual flight delays:

$$TWD\left(\pi_{(S,MPS)}\right) = \sum_{i_k \in S} w_{i_k} d_{i_k} \tag{6}$$

$$d_{i_k} = \sum_{\substack{0 \le m < k \\ i_m \in \pi_{(S,\,MPS)}}} c_{i_m, i_{m+1}} - e_{i_k}, \; 1 \le k \le n \tag{7}$$

where w_i and d_i are the weight (i.e. relative importance) and delay of flight i respectively, and e_i is the earliest possible time that flight i could arrive at the runway threshold.

2.2 Definition of RSP2

RSP2 is the generalization of RSP1 that allows mixed takeoff and landing operations. The cost matrix c_{ij} may now violate the triangular inequality:

$$c_{ij} \le c_{ik} + c_{kj}, \; i,j,k \in S \tag{8}$$

if i and j are landings and k is a takeoff. It may thus be possible to insert one or more takeoffs between succes-

sive landings without stretching their minimum safe separation. This requires the following modification of the TLO and d_i:

$$z_k = \min_{\substack{0 \le m < k \le n \\ i_m \in \pi_{(S, MPS)}}} \{z_{k-m} + c_{i_k, i_{k-m}}\} \tag{9}$$

$$d_{i_k} = z_k \tag{10}$$

2.3 Definition of RSP3

Introducing operations on multiple runways produces RSP3. The cost matrix, augmented to take into account the runway of operation for each of flight, becomes:

$$c_{i,j,r_i,r_j}, r_i, r_j \in R \tag{11}$$

where r_i and r_j are the runways assigned to consecutive flights i and j, and R is the set of available runways. Moreover, the solution has to produce a runway assignment for each flight thus introducing decision variables:

$$x_{ir} = \begin{cases} 1, & \text{if flight } i \text{ is assigned to runway } r \\ 0, & \text{otherwize} \end{cases} \tag{12}$$

Wake vortex effects are eliminated if the landings occur on crossing runways. Time separation has to account only for the time the first aircraft needs to clear the runway crossing point. This time is generally smaller than the inter-landing separation on the same runway, and as a result the triangular inequality is violated just like in RSP2.

2.4 Static versus Dynamic RSP

In contrast to the static RSP versions, described above, in the dynamic RSP , the complete set of flights is not known in advance. New flights must be accommodated as they appear over time. The optimal solution using static RSP may only be found at the end of a busy period, when all the flights are known; too late!

A simple dynamic algorithm updates the tentatively optimal schedule, resolving the static RSP periodically, upon accumulating a number of new requests. More sophisticated algorithms, accounting for the anticipated traffic mix, may be also possible but are beyond the scope of this paper.

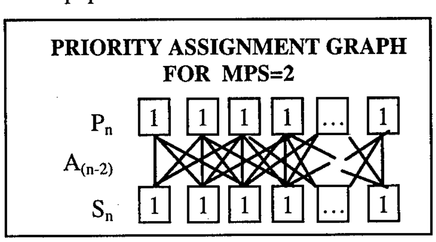

Figure 1: a G_n^2 Priority Assignment Graph

3. The Priority Assignment Graph (PAG)

The Priority Assignment Graph (PAG) is a bipartite graph of the form X_{n-d}^{MPS} defined as:

$$X_{n-d}^{MPS} = (S_{n-d}, P_{n-d}, A_{(n-d,MPS)}) \tag{13}$$

where $S_{n-d} \subseteq S$ and $P_{n-d} \subseteq P$ are disjoint node sets with n-d nodes. $A_{(n-d,\, MPS)}$ is a set of arcs, showing the assignments feasible under the MPS constraints (1):

$$A_{(n-d,MPS)} = \{a_{ij} : |i - j| \le MPS, i \in S_{n-d}, j \in P_{n-d}\} \tag{14}$$

For every value of d, $1 \le d \le n$, the MPS constraints allow X_{n-d}^{MPS} to have a number of possible types. Figure **1** shows the "complete" type: $G_n^2 = (S_n, P_n, A_{(n,2)})$.

The PAG is, by construction, a representation of the MPS-feasible solution space because every complete assignment, i.e. mating of the elements of S with the elements of P, defines a distinct permutation $\pi_{(S,\, MPS)}$ in the FCFS neighborhood.

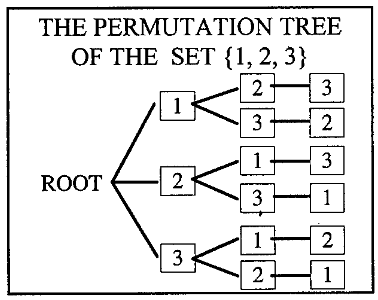

Figure 2: The Permutation Tree

4. The Permutation Tree (PT)

The Permutation Tree (PT) is a complete representation of all permutations $\pi_{(S,MPS)}$. Figure 2 shows a sample PT of the set {1,2,3}. Moving on a path from the root to a leaf, defines incrementally a distinct permutation of S. Nodes at level d reflect ordered subsets with d elements. MPS-feasible nodes map on the set of the PAGs X_{n-d}^{MPS}.

The PT is an important underlying concept, because it helps distinguish between the two types of search for the optimal permutation: the Depth First Search (DFS) and the Breadth First Search (BFS).

5. Branch and Bound (BB) Depth First Search (DFS) on the PT

A Depth First Search (DFS) solution branches down the PT, incrementally evaluating the cost function. When the accumulated cost exceeds the cost of the currently "best" permutation, the search path is bounded ("pruning" the remaining sub-tree) and the solution backtracks in order explore other permutations through un-visited (unmarked) nodes. When a leaf is encountered the currently best permutation is updated.

The effort required by a BB-DFS solution, may be estimated by examining a recursive step. This effort is shown, below, to be exponential in the number of flights for MPS values of 1 & 2 .

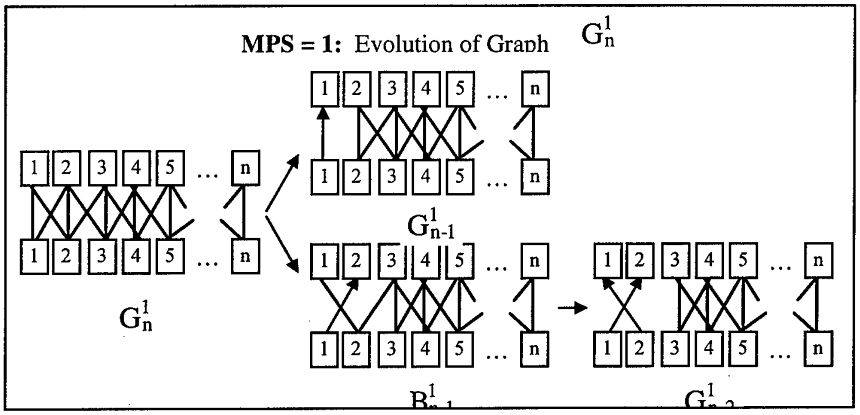

Figure 3: PAG evolution with MPS=1

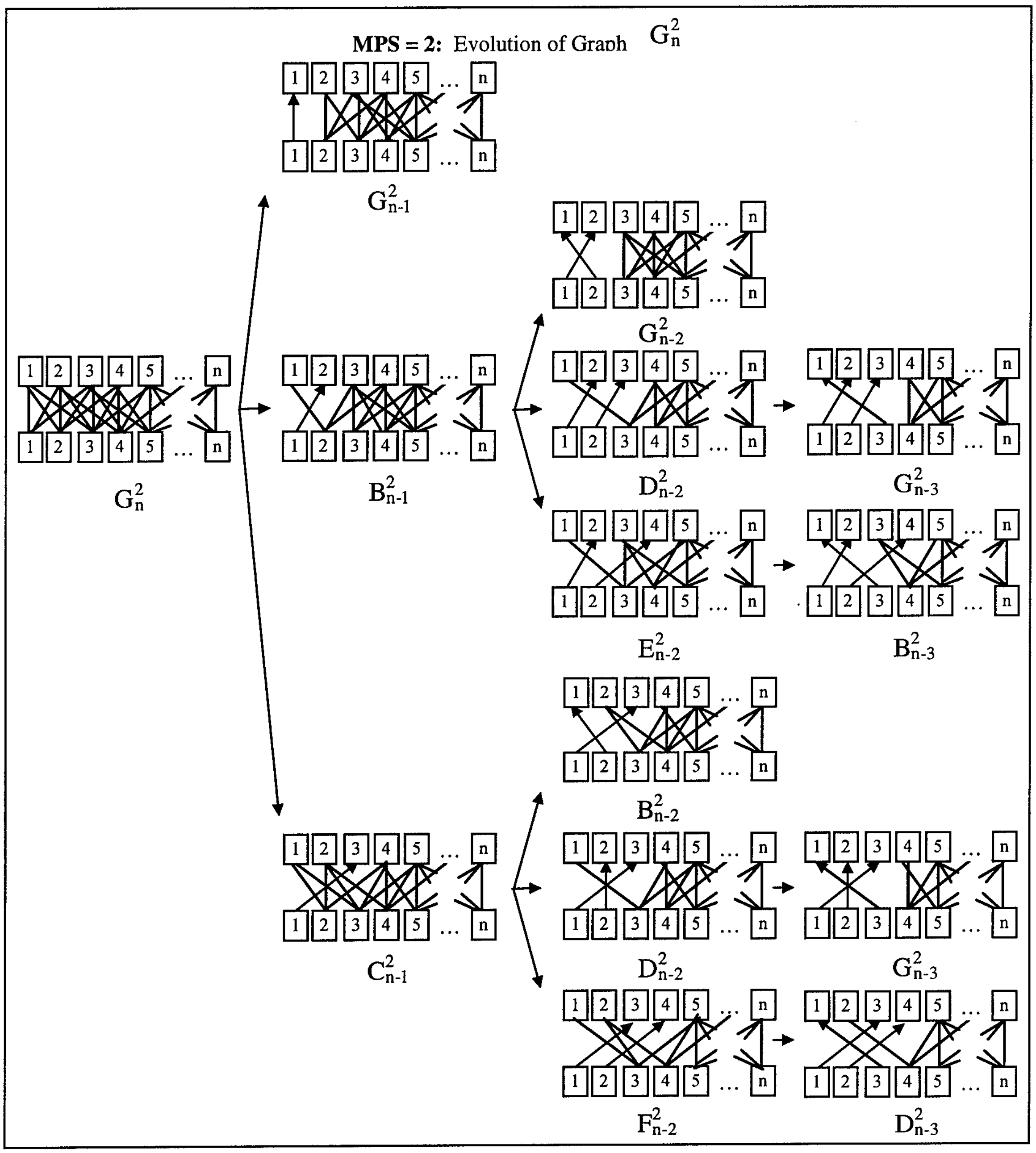

Figure 4: PAG evolution with MPS=2

5.1 MPS = 1

Figure 3 shows the recursive step on the evolution of a G^1_n graph. Assigning flight 1 to slot 1, we get G^1_{n-1}, a graph of the same type with n-1 nodes. However, assigning flight 1 to position 2, results in B^1_{n-1}, different than G^1_{n-1}. where flight 2 may only be assigned to position 1, hence resulting in a G^1_{n-2}. Denoting by g^1_n the effort required to construct a full assignment with a G^1_n, we get from Figure 3 the following well known Fibonacci equation:

$$g^1_n = g^1_{n-1} + g^1_{n-2} + \text{const}$$

whose solution is $g^1_n = c\left(\frac{1+\sqrt{5}}{2}\right)^n$.

5.2 MPS _ 2

Similarly with the case for MPS = 1, Figure 4 shows the recursive steps on the evolution of a G^2_n where 6 graph types coded with letters G, B, C, D, E, F appear. One may safely assume that the BB search for the optimal assignment on the PT requires a worst case computational effort of the form:

$$g^{MPS}_n = c\,(fn_{(MPS)})^n$$

This is an exponential function in the number n of available flights.

6. Number of PAG types

Figure 3 shows 2 graph types X^1_n for MPS = 1, i.e. ($X \in \{G, B\}$), whereas Figure 4 reveals 6 graph types for X^2_n for MPS=2, i.e. ($X \in \{G, B, C, D, E, F\}$). In general the number of PAG types X^{MPS}_{n-d} is given by the following theorem:

Theorem 1:
The PAG types for given MPS = k, when a number d of flights have been selected, correspond uniquely to the MPS-feasible subsets of S, the set of available flights, with cardinality d. The number of these subsets is given by:

$$N_{(MPS=k)} = {}_{2k}C_k = \frac{(2k)!}{(k!)^2} \qquad (15)$$

where ${}_{2k}C_k$ is the well known binomial coefficient.

Proof:
The PAG corresponds by construction to a MPS-feasible subset of S. In order to count the number of feasible subsets with d elements, consider the diagram on Figure 5, showing flights in FCFS order. When stage d satisfies the condition "$n-k \le d \le k$" a feasible subset $S_d \subseteq S$ may be formed by choosing k out of the 2k elements in the range (d-k+1, d+k) as shown in equation (15). Within each of these subsets, there may be up to k+1 optimal permutations (paths on the PT), each of them ending with a different flight j, such that

$$d-k \le j \le d \quad \text{and} \quad i \ne j$$

$$1,2,\ldots,(d-k),\underbrace{(d-k+1),\;\ldots\; d}_{k}\;\;\overset{\substack{\text{Stage}\\ d}}{|}\;\;\underbrace{(d+1),\;\ldots,\;(d+k)}_{k},(d+k+1),\;\ldots,\;n$$

Figure 5: MPS feasible partitions of S with d elements

7. Coding The PAG: The Label Vector

We now drop the arbitrary letter notation, introducing a systematic coding of the PAG and its corresponding feasible subset of S, with MPS-dimensional "label-vectors" defined by theorems 2 and 3 below. Each label-vector determines the elements of its corresponding subset $S_d \subseteq S$, and its evolution, as elements are added to it from its complement subset $\bar{S}_d$.

Theorem 2:
There are ${}_{2k}C_k$ integer k-dimensional label-vectors of the form

$$v = (v_1, v_2, \ldots, v_j, \ldots, v_k) \qquad (16)$$

$$\text{with } k \ge v_j \ge v_j + 1 \ge 0,\;\; 0 < j < k \qquad (17)$$

Theorem 3:
The PAG types for MPS = k correspond uniquely to an equal number of label-vectors defined by equations (16) and (17).

7.1 "Chessboard Proof"

The proof of theorems 2 and 3 derives from the interpretation of label-vectors, as the position deficit of yet not selected flights. This is illustrated using the "Chessboard", a table PAG representation, as shown on Figure 3 and Figure 4 for MPS values of 3 and 5 respectively. Chessboard columns are labeled by the remaining flights in $\bar{S}_d$, ordered in the FCFS discipline, and rows labeled by the remaining positions in the queue. Gray squares denote MPS-feasible flight-position assignments, and stripped squares denote the position or "opportunity" deficit.

7.1.1 Position Deficit

To the left, on Figure 6, the diagonally symmetric chessboard $v = (0, 0, 0)$ corresponds to a "G-type" PAG. To the right, the chessboard $v = (3, 2, 1)$ at stage d=7, with columns labeled by remaining flights 5, 7, 9, 11,... has an asymmetric structure indicated by stripped squares.

Observe that flights 6, 8 and 10 are missing. They have been selected before flight 5 whose only feasible option is now position 8. The position deficit, thus, counts for every remaining flight how many later arrivals have been selected to land/takeoff before it. Similarly flights 7 and 9 have 2 and 1 stripped squares respectively. Clearly, for MPS = k, only the first k remaining flights may have a non-zero position deficit, and therefore the label-vector has only k meaningful positions.

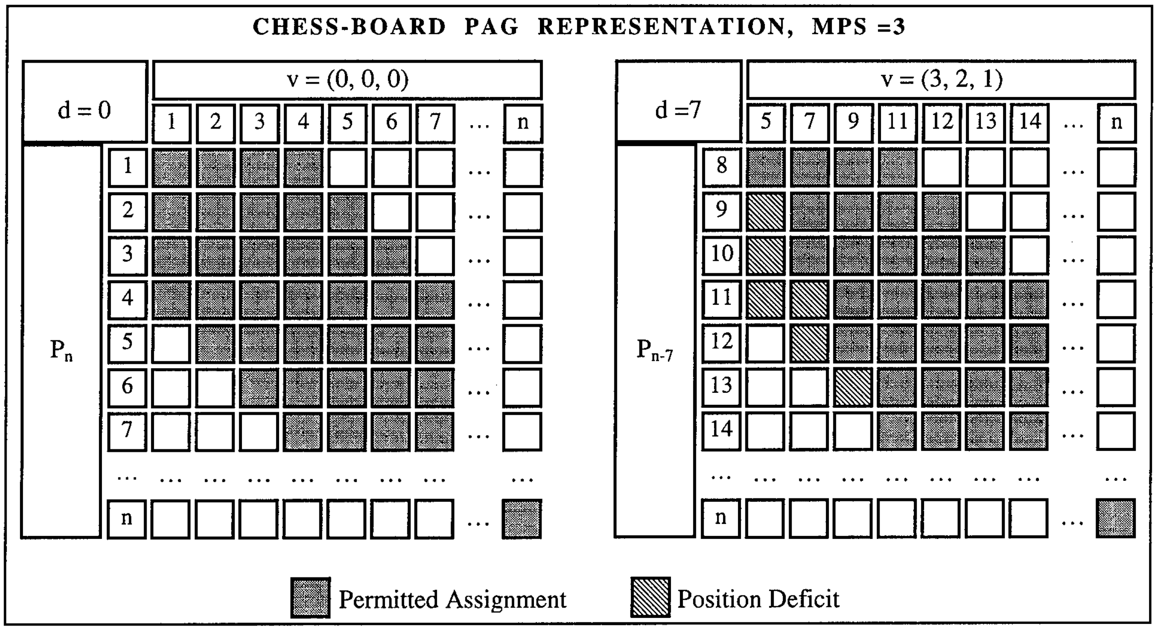

Figure 6: Chess-board PAG Representation

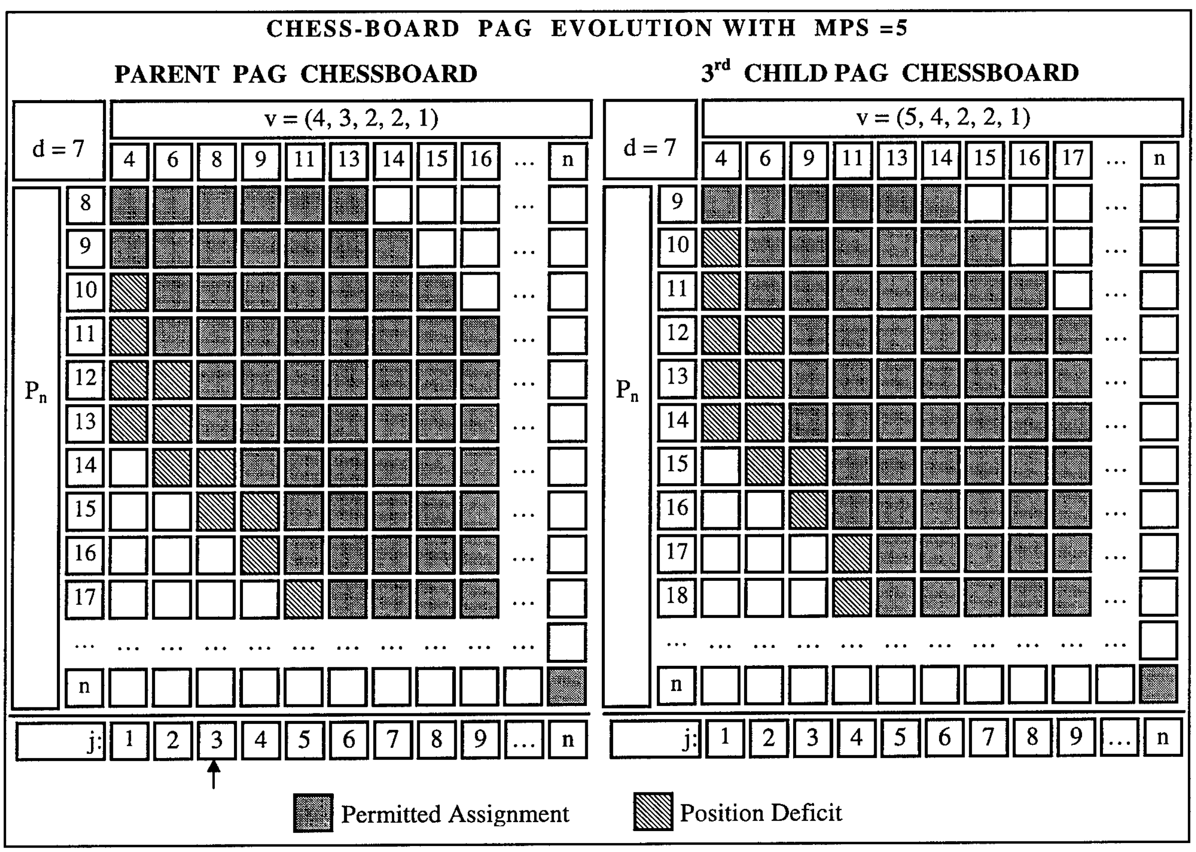

Figure 7: PAG Evolution with MPS=5

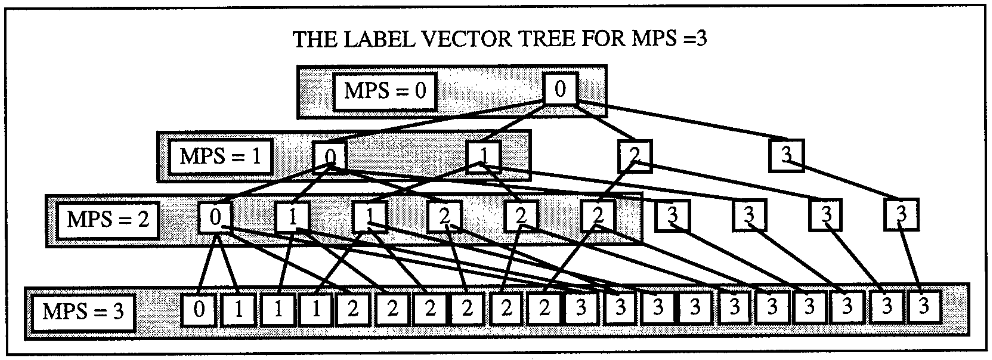

Figure 8: The Label Vector Tree

7.2 Recovery of available flights

Figure 6 and Figure 7 reveal the relation of the set of remaining flights with stage, and label vector. This relation is crucial in the search for the optimal permutation, since for every label-vector at a given stage, it recovers the remaining flight FCFS indices, allowing access to their information record. One may verify from Figure 6 and Figure 7 that the index f_j, of the j^{th} available flight, is given by:

$$f_j = d + j - v_j, \quad 0 \le j \le MPS \qquad (18)$$

$$f_j \le f_j + 1, \quad f_j \in S \qquad (19)$$

7.3 The Flight to Position Assignment Process: The PAG Children

The search for the optimal permutation proceeds by finding the optimal assignment for each of the remaining flights. Equation (18) allows us to identify each of the MPS+1 candidate flights. Removing each of these flights will result in a different chessboard, i.e. a different subset of S. Therefore, every chessboard may have at most MPS+1 feasible descendants, or, "children", whose label-vectors are given by the following theorem:

Theorem 4:

The j^{th} child v^j of a parent label vector v^P is given by:

$$v_i^j = \begin{cases} \begin{cases} v_i^P + 1, & 0 \le i < j \le MPS \\ v_{i+1}^P, & j < i \le MPS \end{cases}, & v_0^P < MPS \\ v_{i+1}^P, \quad 0 \le i < MPS, & v_0^P = MPS \end{cases} \qquad (20)$$

Proof:

Selecting the j^{th} child of label vector v^j means that the remaining flight f_j is chosen to operate next. Clearly flights f_k, with $k < j$, having smaller FCFS index than f_j, i.e. have joined the queue before f_j, have an extra flight jump before them. Therefore their position deficit increases by 1. The remaining child label vector is filled with the position deficits of the remaining flights with FCFS index higher than f_j.

Clearly, equation (20) shows that when the first component of the parent label-vector v^P equals the value of MPS, the first remaining flight has been shifted backwards in the queue as far as possible. Choosing j>0 would result in a child label vector whose fist element would be larger than the maximum position shift.

Corollary:

Label-vectors whose first component equals the MPS value have only one child. All others have MPS+1 children.

7.4 The Label Vector Tree (LVT)

The label vectors may be ordered lexicographically. Moreover, Figure 8 reveals further a tree structure showing a LVT for MPS=3. Tracing the path from each leaf to the root of the LVT produces the components of a distinct label-vector. Notice, that the LVT for MPS=3 contains the LVT's for lesser MPS values, indicated by the shading on Figure 8.

The LVT, is more than a mathematical curiosity, in that it saves memory in storing LVT' s for large values of MPS.

8. The Solution or State Space

As explained earlier, a path from the root to some node at level d of the PT, corresponds uniquely to a distinct ordering of some subset S_d. Lumping all the PT nodes with the same S_d into a "state of computation" $X_{(d,\,v)}$, produces the solution space, where the solution proceeds in an incremental way, eliminating a vast number of paths, keeping only optimal ones.

Figure 9 and Figure 10 show the solution space for MPS values of 1 and 2. Label-vectors code the states of computation, thus providing storage for intermediate results. Theorem 4 determines the arcs in the solution space, which correspond to remaining flights whose indices are given by eq. (18). The MPS constrains limit the number of arcs incident to a state to at most MPS+1.

The solution space is organized in columns of states, called stages of computation. The number of states per stage expands in the first MPS stages from 1 to a maximum of ${}_{2k}C_k$, and contracts in the last MPS stages back to 1.

Incidentally, in a dynamic environment, where new flights are added to the FCFS sequence at random times, the state space may be viewed as a part of an infinite state space. As a matter of curiosity, notice that there is a "dual" to the label vector, corresponding to the complement subset, and to theorem 4, that move backwards (right-to-left) on the solution space.

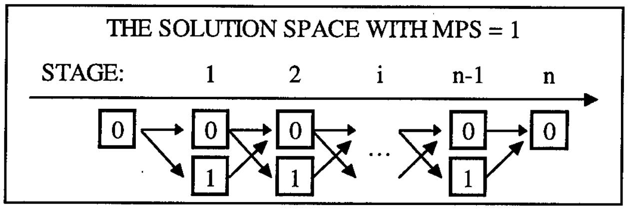

Figure 9: Solution Spaces for MPS=1

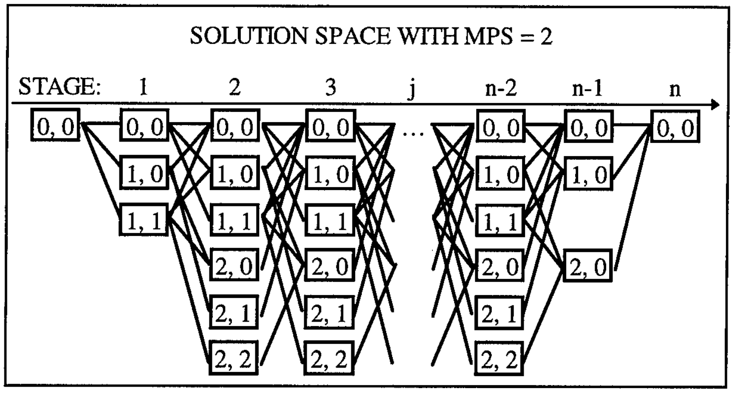

Figure 10: Solution Spaces for MPS= 2

9. Solution by Incremental Shortest Paths

If we think of permutations as pointed lists, each arc coming into a state $X_{(d,v)}$, is a pointer to an optimal permutation of the same subset, whose last element is determined by the origin of the arc and equation (18). One may, therefore, use the notation $(f_i, \overline{X}_{(d,v)})$ to describe each of the incoming arcs to that state where $f_i \in \overline{X}_{(d,v)}$ the complement of $X_{(d,v)}$.

At each stage incoming paths are augmented by one flight. At each state, for each remaining flight $r_j \in X_{(d,v)}$, corresponding to the j^{th} outgoing arc, we produce an optimal permutation $(r_j, \overline{X}_{(d+1,v^j)})$ by appending r_j to the optimal input path $(f_{i^*}, \overline{X}_{(d,v)})$, by choosing i^* that minimizes over i the cost:

$$\min_i \left\{ cost_{(f_i,\overline{X}_{(d,v)})} + c_{f_i,r_j} \right\} \tag{21}$$

At the end of stage $d = n$, the complete optimal path is traced backwards in the solution space.

To help understand this process, we draw the analogy to the incremental shortest paths method. The next flight r_j may be viewed as a city for which we want to find its shortest path to the origin, the root of PT in our case. Input permutations $(f_i, \overline{X}_{(d,v)})$ may be viewed as shortest paths to all the "neighboring cities" of r_j. To find the shortest path from r_j to the root, we need only consider, for each neighbor, the sum of the distance of the neighbor to the origin, plus the distance of the neighbor to r_j.

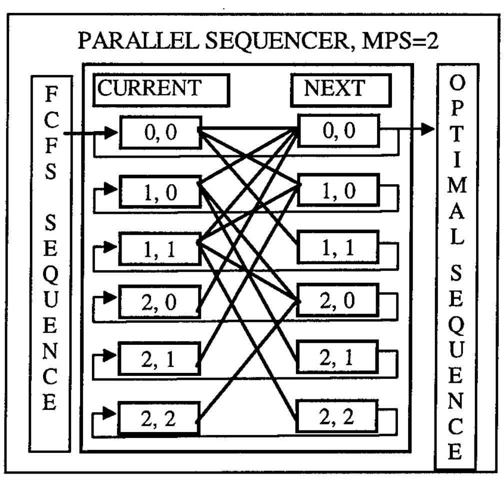

Figure 11: The Parallel Sequencer for MPS=2

10. The Parallel Sequencer

Notice on Figure 9 and on Figure 10:

a) that at each stage, the state computations are independent of each other and may be performed asynchronously and/or in parallel.

b) the "stage invariance" of the solution space whereby label vectors and arc structure remain the same from one stage to the next.

We may therefore, use a computational engine, modeling the generalized cross-section of the solution space, containing only two stages (columns), at a time, labeled as "current" and "next". Stage current contains pointers to the optimal paths with d flights, used to compute optimal paths with d+1 elements collected in stage "next".

This engine, the "Parallel Sequencer", shown in Figure 11 for MPS=2, may use up to ${}_{2k}C_k$ processors, crunching in parallel, to produce the optimal permutation in time linear to n, the number of available flights.

MPS=3: PARALLEL SEQUENCER IN TABLE REPRESENTATION

INDEX	v	ADDRESSEE LIST
0	(0, 0, 0)	0, 1, 2, 3
1	(1, 0, 0)	0, 4, 5, 6
2	(1, 1, 0)	1, 4, 7, 8
3	(1, 1, 1)	2, 5, 7, 9
4	(2, 0, 0)	0, 10, 12, 12
5	(2, 1, 0)	1, 10, 13, 14
6	(2, 1, 1)	2, 10, 13, 15
7	(2, 2, 0)	4, 10, 16, 17
8	(2, 2, 1)	5, 11, 16, 18
9	(2, 2, 2)	7, 13, 16, 19
10	(3, 0, 0)	0
11	(3, 1, 0)	1
12	(3, 1, 1)	2
13	(3, 2, 0)	4
14	(3, 2, 1)	5
15	(3, 2, 2)	7
16	(3, 3, 0)	10
17	(3, 3, 1)	11
18	(3, 3, 2)	13
19	(3, 3, 3)	16

Figure 12: The Parallel Sequencer for MPS=3

Figure 12 shows a table representation of the Parallel Sequencer for MPS=3, as an indexed array of label vectors and "addressee list" i.e. indices modeling the arcs of the solution space.

10.1 Garbage Collection.

The Parallel Sequencer generates a backward pointed tree of "schedule records" that gets pruned along the way to a single leaf.

The vast number of generated intermediate records, which depends on the number of flights considered for scheduling and the value of MPS, may exhaust the computer memory resources. Fortunately, a recursive "garbage collection" algorithm may be used to reduce memory requirements by recycling schedule records after every stage of computation.

11. The Triangular Inequality

The definitions of RSP2 and RSP3 introduce the triangular inequality in the matrix of minimum time separations. The situation is depicted in figure 13, showing schematically a takeoff (T) fitting loosely between two consecutive landings, a heavy L_1 and a light L_3.

The structure of the Parallel Sequencer, deals with this situation, by allowing more than one "optimal paths" to be transmitted along each arc of the solution space. Theoretically, this is equivalent to expanding the definition of the RSP1 optimal "sub- path" from $(f_i, \overline{X}_{(d,v)})$ to:

$$\underbrace{(L_1, T_1, T_2, \dots, T_j, L_2,}_{\text{permutation-suffix}} \underbrace{\overline{X}_{(d,v)})}_{\substack{\text{remaining}\\ \text{flights}}} \tag{22}$$

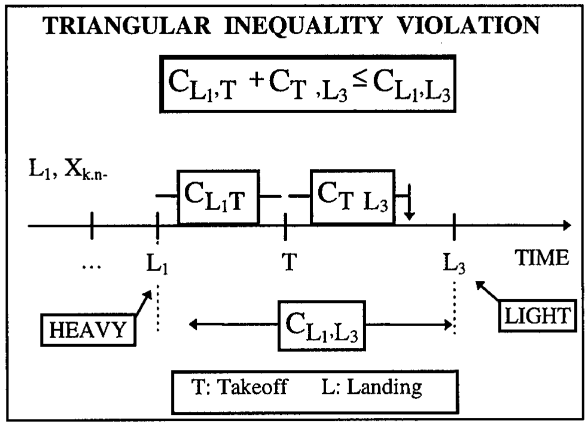

Figure 13: Triangular Inequality

i.e. the state is defined by the ordering of an arbitrary number j of takeoffs up to a previous landing. Notice, that this definition (22) of optimal path in $\overline{X}_{(d,v)}$ implies that there is a secondary optimization taking place between successive landings on the same runway, that puts the included takeoffs in the right order. The incremental cost function used in this case was given above in equations (9) and (10).

12. Conclusions

The static runway scheduling problem has been thoroughly analyzed, producing an optimal, fast and parallel Runway Scheduling algorithm.

Simulation results obtained with real traffic data and airport configuration are very encouraging, showing that even a modest values of MPS=3 produces up to 20% increase in capacity.

Further work is needed in order to:

1. Study the dynamic versions of RSP
2. Get more insight into the real problem through simulation studies.
3. Study the capacity prediction potential, using the RSP solution. Such a tool is useful for global air traffic coordination.
4. Examine the possibility of hardware implementation for the parallel RSP scheduler using 2^{MPS} CPUs.
5. Study the potential application of the Parallel Sequencer, given its efficiency of computation, to other scheduling and routing problems with time-window constraints.

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AIRBORNE CONFLICT DETECTION AND RESOLUTION USING COUPLED FORCES FIELD TECHNIQUE: PRINCIPLES AND RESULTS

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ABSTRACT

This paper presents an airborne conflict detection and resolution logic, based on the coupled forces field technique. This technique defines a general framework for decentralised and reactive coordination for mobile agents. An experiment has been carried out to evaluate this approach. The background, the principles and the application of the technique to air traffic, as well as the principal results are presented.

1. INTRODUCTION

The continuous growth of air traffic[1] raises the recurrent question of the capacity of the air traffic management (ATM) system: (*a*) how to fly more aircraft with the same levels of safety and cost? One may add: (*b*) how to increase the level of safety, or (*c*) how to further reduce the costs of a flight? (*e.g.* delay, route charges). This question should not only be addressed in terms of airspace capacity, but also in terms of control capacity [16].

A possible way to overcome this "capacity barrier" would be to transfer responsibility for separation assurance on board: the aircraft would be equipped with an airborne separation assurance system (ASAS) capable of detecting conflicts, and providing facilities for resolution [3]. Furthermore, providing autonomy of decision for conflict resolution goes in line with the trend of increasing user flexibility in planning preferred routes [9], or operating in a full free-flight manner [15].

The technology will be soon available for the development of ASAS: Automatic Dependant Surveillance Broadcast (ADS-B) will enable the reception of, at least, the *flight state* (position and velocity) of intruders within a range allowing a "sufficient" lookahead time.

However, the airborne ATM approach raises many questions, such as: in what operational conditions could an ASAS be used and provide benefit? Would flow control or strategic planning be necessary, and what could it mean in a free-route context? What would be the role of controllers and pilots, and what type of automation would be acceptable? [11]. These questions are being addressed in the FREER project [7].

The airborne ATM approach also raises theoretical questions. The issue with which this paper is dealing concerns the definition of a logic of detection and resolution, and in particular, the decentralised coordination problem: *how can multiple ASAS involved in the same conflict,* ***individually*** *determine maneuvers that are* ***collectively*** *coherent ?*

In a previous work done at ONERA [17, 18], we have developed a technique that defines a fully distributed and reactive coordination of actions for multiple mobiles. This technique could therefore be applied as a basis for airborne conflict detection and resolution, ensuring coordination of avoidance maneuvers. The CENA has supported a two-year study to investigate and experiment with this technique as a possible ASAS logic.

This paper aims at presenting the principles of the technique, the application, and the results of the experiments. The paper is organised as follows: section 2 outlines the background and the principles, section 3 describes the application to air traffic, and section 4 highlights the main results and shows some typical resolutions.

2. BACKGROUND AND PRINCIPLES

2.1. Related works

The general problem of coordination among multiple mobile agents has been studied in different domains: Robotics, Optimisation, and Distributed Artificial

* This work has been done at ONERA with the support of CENA.

[1] +5.5% per year until 2005 (ICAO sources).

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Intelligence. Various approaches and techniques have been proposed [13, 6].

Most of them rely on a centralized approach [13, 8, 4], and generally address the problem of optimality. The resulting centralized algorithms, however, cannot be distributed onto the aircraft in order to provide them with an autonomous avoidance mechanism. In addition, since they are based upon exploration of "search space", they generally face the well-known problem of combinatory explosion.

The prioritised planning approach has been introduced to overcome this limitation [10]. With this approach, the mobiles determine their own action, one at a time and in order of priority. In the case of a high density of mobiles, however, the lowest prioritized ones may be highly penalized, and furthermore, this computation in sequence may require a long time.

A few approaches implement multiagent planning techniques in order to achieve distributed coordination [2]. However, since these approaches generally require negotiation mechanisms between the agents, they do not allow a reactive and resilient coordination.

Our approach is based on the field of coupled forces technique [17, 18] which is a double extension of the potential field technique [12] used in Robotics for real-time obstacle avoidance.

2.2. Potential field

The underlying idea of the potential field technique is that the robot, represented as a point in its *configuration space*, is a particle moving under the influence of artificial potentials generated by the goal and by the obstacles. The goal produces an *attractive* potential which pulls the robot towards it, while the obstacles produce *repulsive* potentials which push the robot away from them. The negative gradient of the resulting potential defines the (artificial) force to be applied to the robot (Fig. 1).

The repulsive potential U generated by an obstacle is defined so that the robot cannot collide with it. U can be defined as follows:

$$U = \begin{cases} \eta\left(\frac{1}{d} - \frac{1}{d_0}\right) & \text{if } d \leq d_0 \\ 0 & \text{if } d > d_0 \end{cases}$$

where d represents the distance to the obstacle, d_0 the *distance of influence*, and η a constant factor. The repulsive force **F** for this obstacle is derived from U as follows:

$$\mathbf{F} = -\nabla U$$

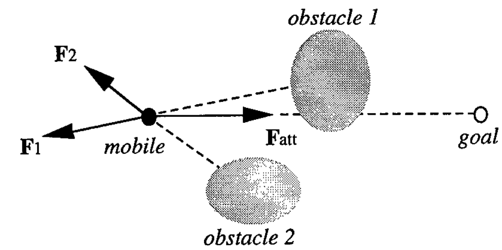

Figure 1. The mobile is repelled by the obstacles (repulsive forces F_1 and F_2) while the goal attracts it (attractive force F_{att}). One can note that the forces are radial since they result from a gradient of distance.

This approach is particularly efficient for situations in which the mobile senses obstacles while moving. The main drawback one has to deal with using this technique is the presence of local minima of the potential function, which prevent the mobile from reaching the goal [13]. These steady states can be induced by the topology of the environment (concave obstacles can easily trap the mobile), but also when several mobiles are moving at the same time. Typically, two aircraft in a "crossing" encounter can easily trap each other (Fig. 2). This problem of steady state leads us to introduce a new force.

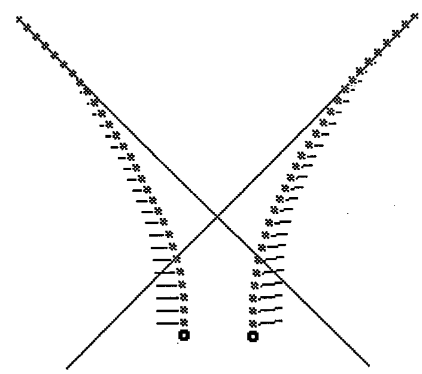

Figure 2. Typical encounter inducing a steady state. The aircraft follow their flight plan (straight line). The repulsive forces are plotted at each point of the trajectories.

2.3. Sliding force field

The repulsive force induces the decreasing of the potential, and therefore, leads the aircraft to descend along the lines of force. The corresponding action is in fact a *fleeing* action (Fig. 3). An *avoiding* action, however, has to induce a move round motion. The underlying idea is to define a force that just maintains the potential constant. This force would lead the aircraft to

slide along the equipotential surface, and thus bypass the intruder (Fig. 3).

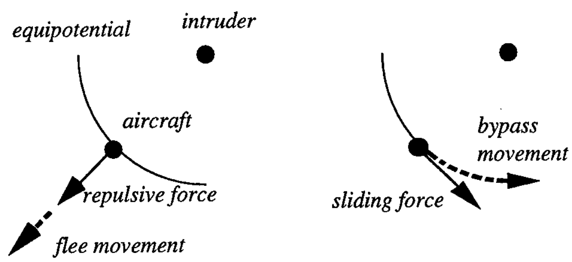

Figure 3. Repulsive vs. sliding force.

A *sliding* force **F** of a potential U is defined by[2]:

$$\mathbf{F}.\nabla U = 0$$

This defines the possible directions of a sliding force (its magnitude is the magnitude of the gradient): any direction located within the tangent plane of the equipotential surface, can be the direction for a sliding force. In fact, these degrees of freedom are essential: they allow the introduction of specific avoidance strategies.

For this purpose, we introduce the following equivalent definition using a reference vector **X**, to be defined:
the direction of **F** *is given by the projection of* **X** *(onto the tangent plane of the equipotential)*

Since the sliding force so defined is the closest one to **X**, this formulation expresses a local minimisation of the deviation with respect to **X**. For instance, by using the velocity vector as projection vector **X**, we minimise the deviation with respect to the current motion (Fig. 4).

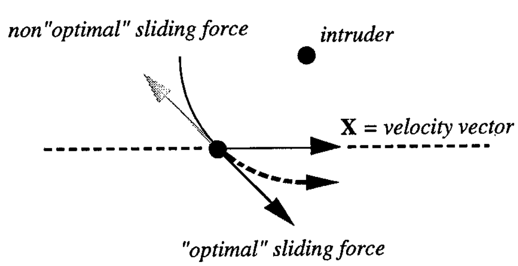

Figure 4. "Optimal" sliding force in 2D.

[2] A similar concept has been proposed in [14] by using a *vortex* field.

Although numerous considerations can be introduced, we will propose a definition for this vector, based on general considerations (section 3).

2.4. Coupled sliding forces field

So far, we have considered the case of an aircraft among passive intruders (*i.e.* aircraft with no avoidance reaction). Let us consider now the case of two cooperative aircraft (A_1 and A_2) that must avoid each other.

We have to define the two sliding forces: $\mathbf{F}_{12}$ exerted on A_1 by A_2, and $\mathbf{F}_{21}$ exerted on A_2 by A_1. For this purpose, we have to first consider the relative forces $\Delta\mathbf{F}_{ij}$ (i, j = 1, 2; i≠j):

$$\Delta\mathbf{F}_{ij} = \mathbf{F}_{ij} - \mathbf{F}_{ji}$$

To define an avoiding action, the relative forces must follow:

$$\Delta\mathbf{F}_{ij}.\nabla U_{ij} = 0$$

where U_{ij} is the repulsive potential generated by A_i on A_j (Fig. 5).

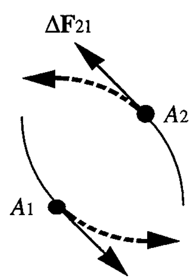

Figure 5. The couple of relative sliding forces (in 2D).

This definition expresses the *coupling relation* between the respective sliding forces of A_1 and A_2. It is important to note that, with no further information, the aircraft cannot dissociate their own force from the relative force. In fact, there are two levels of degrees of freedom:

- as for the previous definition of sliding force (section 2.3), this definition only defines the possible directions of the relative sliding force;
- in addition, since the definition only relies on relative forces, and not on "individual" ones, the definition is less constraining for the couple of "individual" forces (which can be for instance located outside the tangent plane).

The objective is twofold:

- to introduce avoidance strategies,
- to break the coupling in order to allow each aircraft to determine its individual force independently.

In other words, we aim at splitting the system into two simple equations, and introducing strategies is the way to achieve this[3]. This can be done in two steps:

- by requiring the avoidance to be the most "efficient". For this, the magnitude of the relative sliding force must be maximal, therefore, each individual sliding force are opposite, hence located within the tangent plan. This consideration leads to the previous situation of section 2.3;

- then, by requiring a minimal deviation with respect to a given relative vector.

Formally, this can be formulated by:

$$\begin{cases} \text{maximise } \Delta\mathbf{F}_{ij} \quad \text{then} \\ \text{minimise } \Delta\mathbf{F}_{ij} - \Delta\mathbf{X}_{ij} \end{cases}$$

where:

$$\Delta\mathbf{X}_{ij} = \mathbf{X}_i - \mathbf{X}_j$$

with $\mathbf{X}_i$ the projection vector of aircraft A_i as defined in section 2.3.

Finally, the coupled sliding forces are defined independently by (Fig. 6):

the direction of $\mathbf{F}_{ij}$ is given by the projection of $\Delta\mathbf{X}_{ij}$ (onto the tangent plane of the equipotential of U_{ij})

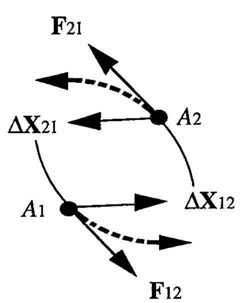

Figure 6. The couple of sliding forces (in 2D).

In the case of multiple intruders, the aircraft just sums up the forces generated by each intruder.

This technique defines a decentralised and reactive coordination mechanism: the forces are issued by each aircraft, only based on information needed by the potential (relative position in case of a parameter of distance) and by the projection vector (*e.g.* velocity vector). In other words, the complementarity is achieved with no explicit coordination (Fig. 7).

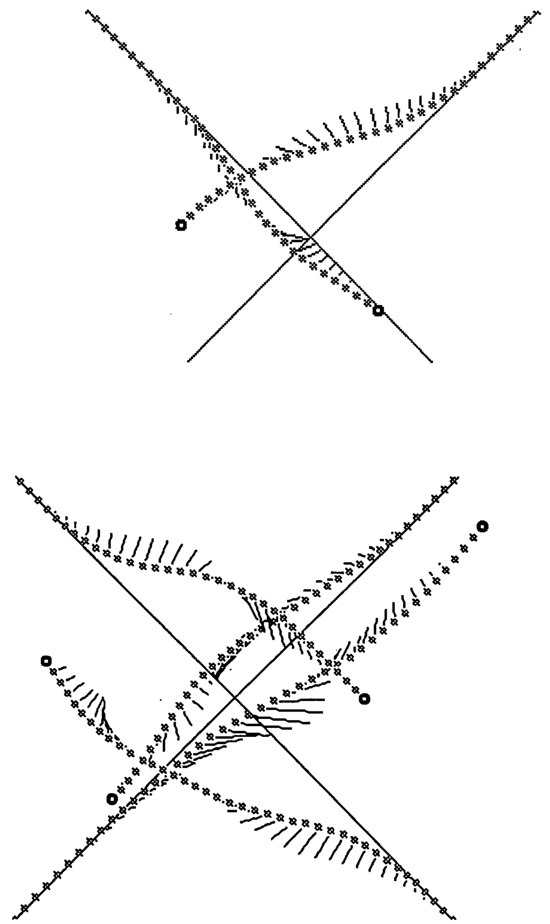

Figure 7. Simulation of encounter with coupled sliding forces (2D). The projection vector used is the relative velocity vector. The first simulation corresponds to the same encounter as (fig 2): the coupled sliding forces enable an avoidance movement.

3. APPLICATION TO AIR TRAFFIC

This section aims at presenting the application of the technique as an airborne logic of detection and resolution.

We will first describe how the notions of repulsive potential and sliding force can be applied. Then, we will briefly depict the overall behavior of the logic.

[3] We assume in the following that the two gradient vectors are collinear (which is the case with gradients of distance).

3.1. Conflict Detection

The objective of conflict detection is to predict the risk of conflict[4] between an aircraft and intruders. This risk can be expressed as a repulsive potential.

In the usual formulation of the potential field technique (section 2), the parameter used for the repulsive potential is the current distance between the mobile and the obstacle. In air traffic however, because of the high velocity of the mobiles, anticipating becomes essential.

For this purpose, we have investigated a formulation based on approaching velocity [17]. However, aircraft flying head-on (high approaching velocity) on parallel routes separated at the minimal separation (low distance), generate a non zero potential. Therefore, this induces excessive detection.

An alternative way to handle high speeds is to use the *Closest Point of Approach* (CPA), by extrapolating the current positions of the mobiles to the point of minimal *distance*[5].

This 3D distance is related to minimal separations. We thus have defined an "elliptic" distance which integrate the difference between minimal separations in the two dimensions. This elliptic distance e_{ij} between aircraft A_i and A_j is defined as follows:

$$e_{ij}^2 = h_{ij}^2 + \rho^2 v_{ij}^2$$

where h_{ij} represents the horizontal (Euclidean) distance between A_i and A_j, v_{ij} the vertical one, and:

$$\rho = \frac{h_{sep}}{v_{sep}}$$

with h_{sep} and v_{sep} the minimal separations. The CPA is deduced from the time before attaining CPA (Δtcpa), defined by:

$$\frac{d}{dt}(e_{ij}(t)) = 0$$

The risk of conflict is a function of the distance between the mobiles at this extrapolated point:

- if this distance falls below the minimal separation, a risk occurs,
- if the distance is greater than the minimal separation plus margins (to be defined), no risk will normally occur.

However, maximal and minimal lookahead times should be introduced. Indeed:

- since the risk prediction is based on extrapolation, a high lookahead time (*e.g.* 20 minutes) would lead to an erroneous prediction (the imprecision grows with time) and therefore may induce false alarms (*i.e.* excessive detection);
- on the other hand, if the time is too short, conflicts cannot be avoided.

In addition, upper and lower thresholds of distance and time also allow a gradual progression in the risk prediction.

Therefore, the prediction of a conflict is based on the combination of two parameters: (1) distance at CPA and (2) time until CPA[6]. Formally, the potential function is defined by:

$$U = u(e(t + \Delta t_{cpa}), e_0, e_1)\, u(\Delta t_{cpa}, t_0, t_1)$$

where u is a normalisation function:

$$u(x, x_0, x_1) = \begin{cases} 1 & \text{if } 0 \le x \le x_0 \\ \left(\dfrac{x_1 - x}{x_1 - x_0}\right)^r & \text{if } x_0 < x < x_1 \\ 0 & \text{if } x_1 \le x \text{ or } x < 0 \end{cases}$$

and t_0, t_1, e_0, e_1 are the upper and lower thresholds of time and distance, and $r \geq 1$. These values will be determined by experiment.

The risk of conflict varies continuously between two values:

- U = 1, the risk is maximal: the distance at CPA violates separations[7] and the minimal lookahead time is reached. This should never happen;
- U = 0, the risk is null: either the distance at CPA is large enough, or the lookahead time is higher than the maximal threshold.

3.2. Conflict Resolution

The objective of conflict resolution is to determine a direction which avoids conflicting intruders. This direction can be defined as a sum of sliding forces corresponding to each intruder. In case of a cooperative intruder, the two sliding forces (of the intruder and of the subject aircraft) are defined as coupled sliding forces.

---

[4] A conflict occurs when the horizontal *and* the vertical distance between two aircraft falls below minimal separations, generally 5 nautical miles (NM) horizontally, and 1000 feet (ft) vertically.

[5] We have investigated this approach, also used by the TCAS logic in vertical dimension [5], after discussions with J. Bourrely and C. Aumasson from ONERA.

[6] In case of very low convergence encounters, the time before CPA may be high while aircraft may be already in conflict. To handle these situations, we have implemented two solutions: reintroduction of the current elliptic distance as third parameter, or use of the time before loss of separation instead of time before CPA.

[7] By using the elliptic distance as risk criterion, the volume of minimal separation is slightly different from the usual one.

For the sake of simplicity, we will focus on what is mainly specific to the application: the definition of the projection vector[8].

To define this vector, we have introduced two considerations:

- selecting the direction which increases the distance at the CPA[9],
- taking into account the limitations of movement (*e.g.* resulting from kinematic constraints).

In the case of kinematic and environnemental constraints (*e.g.* conflictual and non conflictual intruders, forbidden zones), these limitations can be modelised by a *constraint vector* such that [18]:

- its magnitude reflects a degree of constraint (the more constrained the aircraft, the greater the magnitude),
- its direction represents a direction of minimal constraint.

In fact, this vector can be defined as the negative gradient of a *potential of constraint.*

Therefore, the projection vector results from the combination of two components:

- the relative position at CPA,
- the relative constraint vector.

Since the magnitude of the constraint vector is between 0 and 1, the relative position at CPA is related to the minimal separations. Precisely, the projection vector is defined by:

$$\Delta\mathbf{X} = \Delta\mathbf{K} + M_{sep}\,\mathbf{P}_{cpa}$$

where $\Delta\mathbf{K}$ is the relative constraint vector, where $\mathbf{P}_{cpa}$ is the relative position at the CPA, and:

$$M_{sep} = \begin{pmatrix} \gamma_{sep} & 0 & 0 \\ 0 & \gamma_{sep} & 0 \\ 0 & 0 & \nu_{sep} \end{pmatrix}$$

with $\gamma_{sep} = 1/h_{sep}$ and $\nu_{sep} = 1/v_{sep}$ [10].

3.3. Description of the logic

The logic is based on position and velocity (flight state) of the intruders, and provides the pilot with advisories for vertical and/or lateral avoidance maneuvers. A maneuver consists in:

- a lateral and/or vertical direction (*e.g.* turn right and climb),
- an intensity associated to each direction (*e.g.* 10° bank angle and 1600 fpm).

The logic is basically incremental and continuously updates the advisory at each cycle (in particular, updates the intensities).

The overall behavior is similar to the ACAS one [5]:

- when a risk of conflict occurs, the logic issues an avoidance maneuver advisory (corrective mode),
- once the *real* risk (risk of conflict) is eliminated, but while a *potential* risk (risk of getting again into conflict) still exists, the logic proposes a progressive and partial resumption of navigation (preventive mode),
- then, once there is no risk of coming into conflict (during the lookahead period), the logic generates a "clear of conflict"[11].

The information required for each intruder is the following:

- relative position and velocity vectors (3D),
- status (passive or cooperative),
- constraint vector if cooperative.

This information has to be broadcasted by each aircraft.

The logic is capable to handle multiple intruders, passive and cooperative (*i.e.* same avoidance logic). Theoretically, the coherence of maneuvers between cooperative intruders is ensured without explicit coordination. However, in some cases (when the direction of a projection vector is "close" to the direction of the gradient), imprecision may induce conflicting maneuvers. In such cases, a coordination mechanism has been introduced.

4. EXPERIMENTS

The objective of the experiments was twofold:

- tuning the parameters of the logic (in particular thresholds of time and distance), and evaluating statistically the performances,
- analysing qualitatively the behavior of the logic on typical encounters.

For this purpose, the logic has been implemented and integrated into the CENA's platform for ACAS evaluation (OSCAR).

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[8] For historical reasons, we have kept a gradient of distance for defining the direction of the force.

[9] In the initial implementation using the approaching velocity, we used the relative velocity vector.

[10] In the current implementation $\gamma_{sep} = 0$.

[11] The generation of the advisories is not described in this paper.

4.1. Statistical Evaluation

4.1.1. Conditions

The evaluation is based on a model of encounter derived from the MITRE model used for ACAS evaluation [19][12]. This probabilistic model, which defines encounters with two aircraft, was implemented, and 10,000 encounters were generated for evaluation.

In addition, the CENA proposed the use of reduced separations: 2 NM horizontally and 1000 ft vertically. The basic assumption is that the precision of positions and the reaction time would be probably better than with the current ground ATM.

OSCAR allows modelling of pilot reaction time, however, it was decided to use a zero delay (*i.e.* the evaluation was carried out as if the logic were used in an automatic system).

4.1.2. Results

The evaluation was divided into two steps. The first concerned safety: the logic must resolve a maximum of conflicts, but should trigger avoidance maneuvers only when necessary.

The second step addressed the question of cost: in order to reduce deviations while not inducing a new conflict, when should the logic switch to preventive mode, and then generate the "clear of conflict"?

For the safety aspect, we measured the rate of resolved conflicts as a function of the *false alarms* rate (*i.e.* the logic triggers a resolution while separations are respected), by varying the time (t_0, t_1) and horizontal distance thresholds (h_0, h_1)[13] as follows:

h_0 varies from 0.5 to 2 NM by step of 0.125 NM,

t_0 varies from 0.5 to 2 minutes by step of 0.5 minute,

the upper thresholds are deduced from lower ones by:

$$x_1 = 2x_0$$

where x = t or h.

For the time lower threshold of 1 minute (upper threshold is 2 minutes), the curve is the following (Fig. 8):

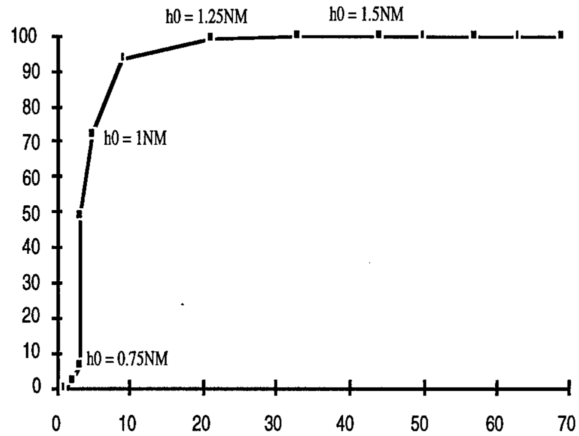

Figure 8. Rate of resolved conflicts (%) as a function of false alarms rate (%) for a lookahead of 2 minutes. Some values of distance threshold are indicated.

One can note from this result that the rate of resolved conflicts increases with distance threshold, nevertheless, the false alarms rate also increases.

To resolve 100% of conflicts with the lowest distance threshold, the time thresholds are the following:

t_0 (minute)	h_0 (NM)	false alarms[14] (%)
0.5	1.75	56
1	1.375	33
1.5	1.25	21
2	1.25	21

Providing a higher lookahead time allows the reduction of distance threshold, hence the false alarms rate. However, an interesting result is that a lookahead of 4 minutes (t_0 = 2 mn) did not provide any benefit: the false alarms rate did not decrease. In fact, since we did not incorporate imprecision in the experiments, the actual rate would probably be higher.

Based on the set of parameters (t_0 = 1 mn, d_0 = 1.375 NM), the mean cost induced by the resolution is the following:

[12] Due to the parameters used in the initial model, most of the encounters were conflictual. To measure the rate of excessive resolutions, a greater distance between aircraft at the CPA was used, which gives approximately a 50-50% division between conflictual , and non conflictual encounters.

[13] The thresholds of vertical distance are deduced from the "elliptic" relation.

[14] This rate corresponds to the number of false alarms, related to the number of cases where separations are respected. Another measure was introduced: the false alarms rate from the pilot's point of view: number of false alarms related to the number of times the logic triggers. For the second line (33%), the pilot's rate of false alarms is 27%.

horizontal deviation	1.50 NM
vertical deviation	623 ft
heading difference	27.7°
vertical speed difference	176 fpm

4.2. Qualitative Analysis

The CENA has defined 84 typical encounters for qualitative analysis. We have also defined some multi-intruders encounters, which seems difficult to solve but which are not necessarily realistic.

During the development of the logic, these encounters were used to improve various features of the resolution process (*e.g.* management of low convergence encounter). Subsequently, the objective was to analyse the behavior of the logic, and to ensure that it behaved properly for these encounters.

To illustrate the behavior of the logic, we have selected two typical encounters.

For each snapshot, the upper area is a (x, y) view graduated in NM, and the lower area is a (z, t) view graduated in *flight level* (100 ft) and second.

Each aircraft starts at the point labelled "0", and a mark is plotted every 2 minutes. The bold lines between trajectories represent the line of the "physical" CPA (*i.e.* based on Euclidean distance).

The first snapshot corresponds to an encounter of two aircraft converging at 90° and at the same altitude. Initial and modified trajectories are represented on the same snapshot.

Each aircraft receives from its own logic a red order (MTE) which corresponds to a corrective maneuver (*e.g.* climb n fpm, and turn with bank angle m): the logic takes control of the aircraft. After a certain delay, a green MTE is issued, corresponding to a preventive maneuver (*e.g.* don't turn left and don't descend). A progressive resumption of trajectory is started. Finally, the "clear of conflict" (COC) is generated, and control is returned to OSCAR (the difference between x and y deviation results from different x and y scales).

The second snapshot corresponds to a 4-aircraft encounter. The aircraft are converging at the same altitude. The corrective advisories are the following:

aircraft	heading (°)	hor. advisory	vert. advisory
1	90	TR (turn right)	CL (climb)
2	210	TR	
3	280	TR	DES (descent)
4	360		

The distances measured at the physical CPA are the following (time at CPA is in seconds, horizontal distance (h) in NM, and vertical (v) in ft):

couple	initial trajectories			modified trajectories		
of a/c	time	h	v	time	h	v
1-2	300	0	0	302	3.16	821
1-3	300	0	0	296	4.92	1739
1-4	282	3.54	0	278	2.26	658
2-3	300	0	0	292	1.77	908
2-4	305	4.83	0	307	3.85	2
3-4	321	3.22	0	347	0.63	1456

One can note an increase in distance at the CPA on the modified trajectories.

5. CONCLUSION AND DISCUSSION

The general concept of repulsive potential and coupled sliding forces provides a powerful framework for airborne detection and resolution of conflicts. The technique allows the definition of an avoidance logic based on flight state, which ensures a reactive coordination with multiple intruders, and issues lateral and vertical maneuvers.

The experiments show that it is possible to resolve all the conflicts of the 10,000 encounters generated, with a "reasonable" cost. In addition, the simulation highlights that the logic is capable of handling the 84 typical encounters defined by the CENA.

However, the experiments also highlight that the *intent* of aircraft should be available, at least for detection to reduce false alarms. In addition, the main feature of the logic is its ability to handle multi-intruder encounters. Such encounters have been created and the logic behaves properly, but a systematic experiment have not been done (some results regarding density can be found in [1]).

Beyond these points concerning this particular logic, there is a major question of what an ASAS should do.

For a logic based on flight state (FS):

- the lookahead time should be optimised to reduce false alarms (around 2 minutes),
- outputs are avoidance maneuvers, displayed on the primary flight display (PFD),

- these maneuvers are to be executed rapidly by the pilot (or sent to the autopilot) with no real man-machine interaction.

This approach of FS based ASAS is probably sufficient for separation assurance with few resolution occurrences (*e.g.* in low density), or for pre-tactical airborne ATM operations (*e.g.* electronic crossing, in-trail climb or descent).

In an en-route context with possibly several conflicts during the flight, it would be necessary to provide a real management of flight *versus* resolution, with a real human centred automation. For this purpose, it is necessary to [7]:

- provide a longer lookahead time (*e.g.* 6-7 minutes),
- output conflict-free trajectories on the navigation display (instead of avoidance maneuvers on the PFD),
- send the "best" one (*e.g.* from the pilot point of view) to the flight management system (FMS).

However, this requires the trajectories of intruders as input, and therefore requires:

- a range of 150 NM,
- the broadcasting of trajectories (or trajectory change points, TCP),
- an FMS guidance so that the own trajectory broadcasted is the actual one.

The Eurocontrol FREER project[15], in which the author is involved, aims at addressing this question of definition and use of a TCP based ASAS.

From a theoretical point of view, while the logic of a FS based ASAS would be derived from a distributed action coordination technique, the logic of an TCP based ASAS would be derived from a distributed trajectory planning technique (*e.g.* using the prioritized planning approach).

These two approaches can be seen as different levels of ASAS: a minimal level for FS based ASAS (which would probably have a lower equipment cost), and an extended level for TCP based ASAS. The question is: Is a "minimal" ASAS promising? If so, can it be made compatible with an extended one? If not, could the FS based avoidance logic presented be better used as an ACAS logic providing lateral advisories?

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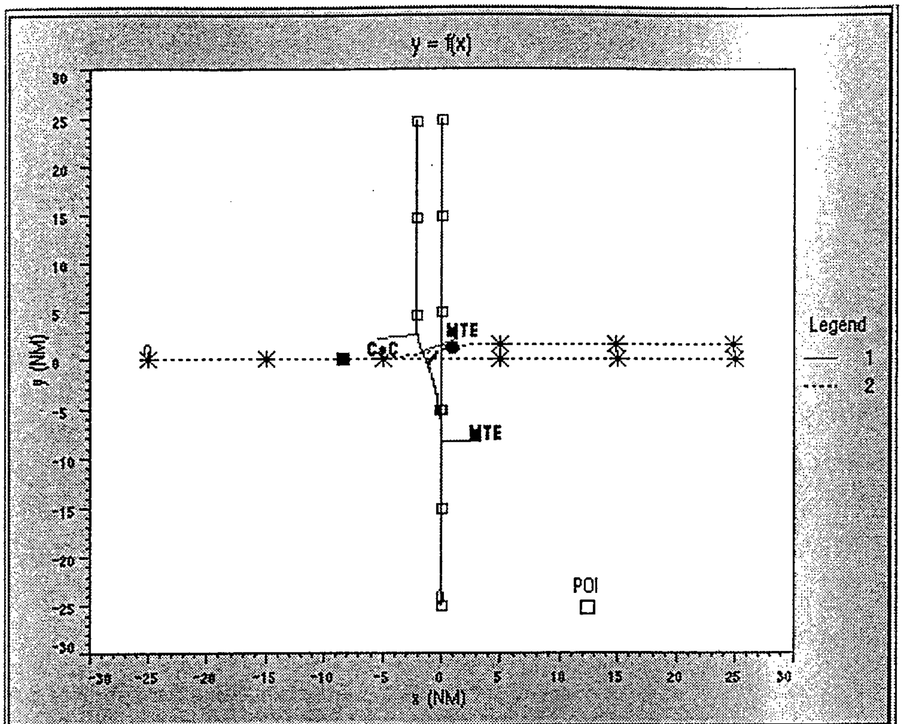
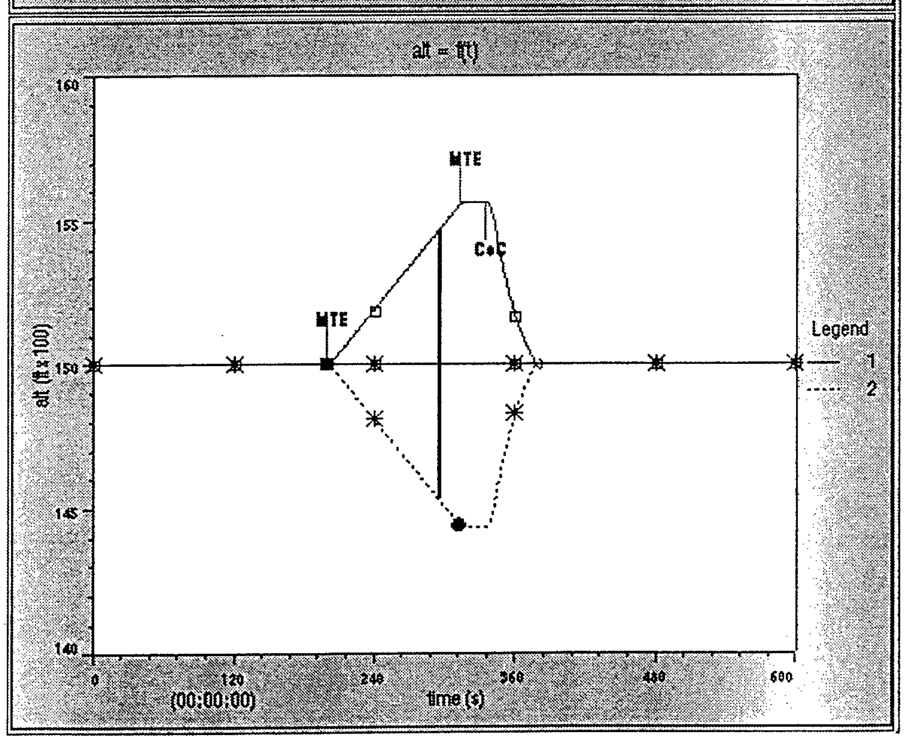
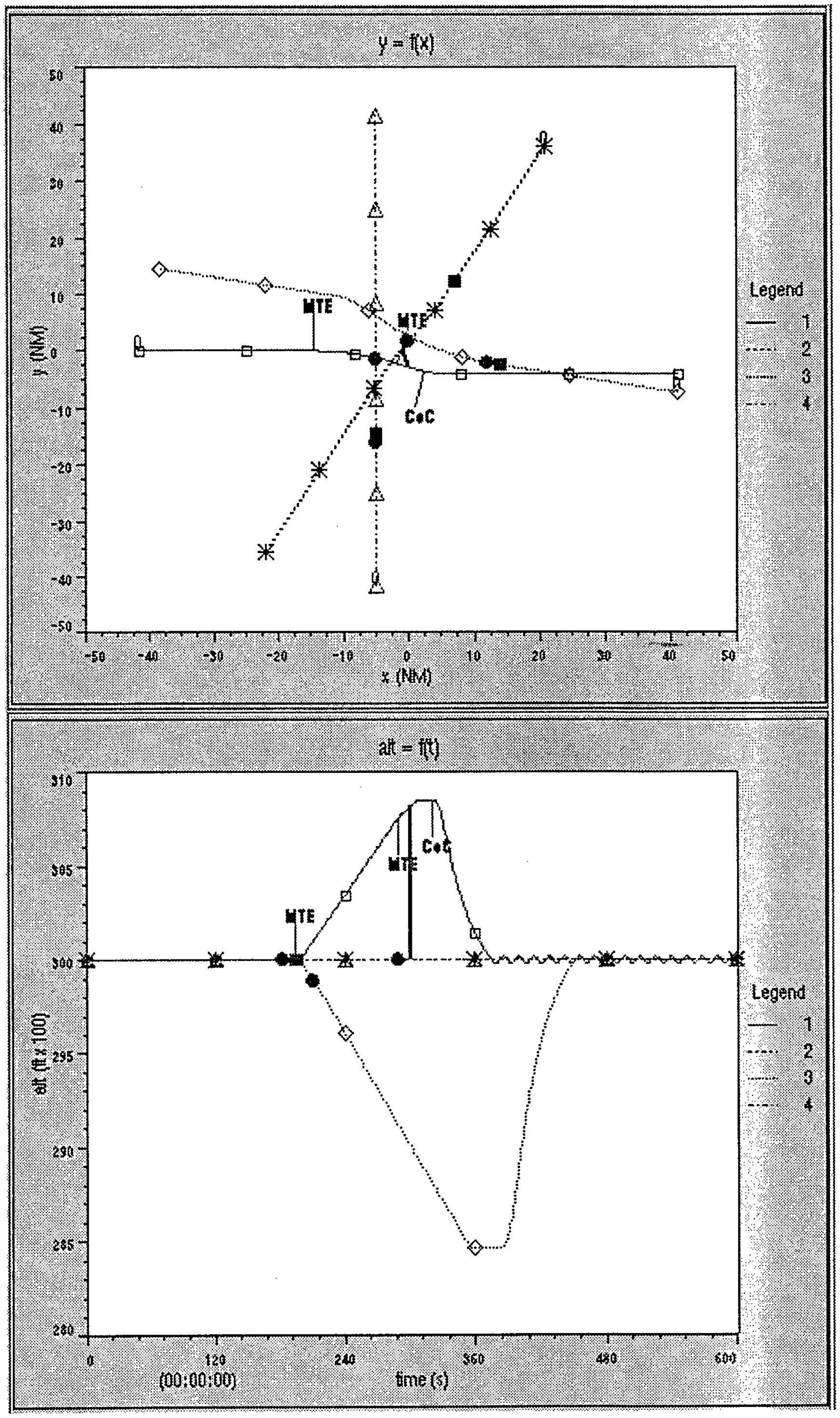


y = f(x)
y (NM)
x (NM)
CoC
MTE
MTE
POI
Legend
1
2



alt = f(t)
alt (ft x 100)
time (s)
(00:00:00)
MTE
MTE
CoC
Legend
1
2


y = f(x)
MTE
MTE
CoC
Legend
1
2
3
4
y (NM)
x (NM)
alt = f(t)
MTE
MTE
CoC
Legend
1
2
3
4
alt (ft x 100)
(00:00:00)
time (s)

HUMAN-MACHINE INTERFACE (HMI) IN THE MAGYAR AUTOMATED AND INTEGRATED AIR TRAFFIC CONTROL SYSTEM (MATIAS)

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Preface

The Hungarian Air Traffic and Airport Administration/Légiforgalmi és Repülőtéri Igazgatóság is to replace the current Budapest Area Control Centre (ACC) with a new, purpose-built building at Ferihegy Airport.
The new ACC system is planned to be fully stripless and will include area control, terminal area control, aerodrome control, military control and flight information sectors.

Readers involved in air traffic control may find it interesting, how the system is planned to fulfill the controllers' requirements.

The article contains the description of those functions, which are planned to be used by the operational staff in the OPS Room, so the technical and maintenance windows are omitted. The windows of the radio and telephone systems are also omitted.

Project history

The new Air Traffic Control Centre will accommodate all those functions already contained within the current ACC with the addition of Approach Control Services, Flight Information Centre and Military Control sectors.

The current facilities are unable to cope with the traffic demand, the current Area Control Centre cannot be upgraded.

The building was finished last year. It is located near the threshold of RWY 13R at Ferihegy aerodrome. It has an approx. 700 sq. m OPS room.

In 1993 an Operational Outline Plan was worked out with the assistance of the Eurocontrol Advisory Service, which has been requested to support continuously the project. Controllers have been involved also in the preparation of the OOP and also in the drafting of the tender requirements. A two-phase tender was called, which was finally won by the Siemens ATM. The signature of the contract took place in October 1995.

The operational start date of the MATIAS is some time in 1999.

Roles and HW

The following roles and HW is planned for the sectors in the MATIAS:

ACC, APP an MIL sectors:
  one 2x2 K and one 1 K display for the EXE and an other same set for the PLN controller
FIC sectors:
  two 1 K displays for the EXE and an other same set for the PLN
Aerodrome Controller:
  two 1 K Barco displays
Ground Controller:
  one 1 K Barco display
Flight Data Section:

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

one 1 K display for each operator (the FD section consists of FPL operator, EST operator, COM operator and AIS operator roles),

Operational Supervisor:
two 1 K displays

Team Chiefs:
one 1 K display

The workstations will be supplied with a 3-button mouse and a keyboard.

Main HMI requirements

A stripless system was required in the tender. Flight lists were planned for all roles. As one of the main function of the strips is to assist the controllers in detection of conflicts, using flight lists alone requires the MTCA facility.
Data input via radar labels and flight lists are planned with pop-up menus and scrolled lists,
Different colours are used to indicate assumed, concerned, unconcerned traffic, data under coordination, e.t.c.
An integrated display system was planned where all data, regardless if it is radar data, flight plan data or information can be displayed on the same screen.
The same functionalities were required for the EXE and for the PLN controllers.
The HMI was required to be easily modifiable.

MATIAS windows

During the past year we have defined the window requirements which have been handed over to the factory for review and comment. It should be mentioned, that the HMI was planned by those personnel who will actually use the system.

The followings have been taken into consideration during the HMI definition:
- ODID experiments,
- results of a real-time simulation of the MATIAS carried out in Brétigny in 1995,
- HMI in Maastricht
- planned HMI of the Finnish FATMI System.

Some of the MATIAS HMI functionalities had to be worked out without adequate basis, as e.g.:
- Flight lists for TWR controllers have not been developed so far,
- Military and FIC sectors have not been included in the samples,
- Different coordination methods are used with neighboring units, OLDI links in some directions, while the coordination is verbal to other directions.

General features

The following general features have been defined for the windows:

The windows will be moveable, closeable, scrollable, resizeable and iconizable by the operator and dynamically resized by the system.

No requirement exists for windows to be switchable from one monitor to an other.

Priority swap function will be provided.

Some windows will be regarded as “critical”. These windows will be raised automatically when any other window overlays them, in order to prevent important data being obscured.

Some windows will be transparent windows on the radar window (Stack Window and Coastlist Window).

The windows can be in full access mode, restricted access mode (read only) and in no access mode, depending on the operator’s role.

Different colours are planned for flights in:
- assumed status (the flight is under the control of the sector)
- “concerned “ (the flight is within the sector but controlled by an other sector e.g. the flight is released),
- non-concerned or non-correlated
- advanced information, (the flight will be under the control of the sector).

In such cases the flight data line and the whole track label will be in different colour. Colours indicate also the warnings and data under coordination, when the relevant field will be in different colour.
The alerts and warnings will be categorized with respect to their severity, as follows:
1. Severity 1 Warning, highest priority, requiring immediate attention by the user (same colour as for severity 2, but blinking)
2. Severity 2 Warning, high priority (unique colour)
3. Severity 3 Warning, low priority (unique colour)

The pointing device will be switchable for left-handed and right-handed users. There will be Action button, an Information button and a Window Manager button.
By default, the left-hand button of the device will be the Action button.

The pointer can take different shapes. It indicates if:
- it is in window management state or the window should be re-sized,
- no input allowed
- action required
- system busy
- normal

Center cursor function was also required.

Categorization
The MATIAS windows can be categorized as follows:

General windows,
Radar windows,
Flight List windows,
Flight Plan windows (including the Coordination Window and the conflict windows, as well),
Information (or AIS) windows,
Sectorisation windows,
Communication windows,
Menus and scrolled lists

The windows can be invoked from various menu bars i.e.: Global menu, COM bar, RAD bar, FDP bar and AIS bar.

General windows
Every display has a Global Menu. Different Global Menus exist for the large screens and for the small screens. The Global Menu allows the following functions:

Sign-on, Change password
Selection of left-handed or right-handed operation
Access to COM, AIS, FDP and resectorisation functions,
Situation (Radar) Display presentation
Hard-copy printout of a window or sector traffic
Selection of customisation sets
Brightness control
Display of additional flight lists
Display of alerts. It should be noted, that all alerts, regardless of the originating subsystem will be displayed via the Global Menu.

The main important general windows are:
Sign-on Window,
Brightness Control Window
Alerts List Window, Message Window,
Alerts entry window (for AIS OP role)

Radar windows
Maximum 3 independent radar windows can be presented on the large screens. One radar window can be displayed on the small monitors, however altogether 3 radar windows can be open in a large display + small display configuration.

The main radar window on the large screen can not be switched-off by the operator.

Radar bar functions:
The following functions can be selected from the radar bar:

Primary plot presentation for a selected display

Map information to be presented (the local maps are role dependent). The operator is also able to create local map with a graphics editor
The supervisor is able to initiate the presentation of danger area maps, military area maps, e.t.c. centrally.
Display of separation rings around radar tracks on the main radar window.
Display of weather conditions in the selected radar window.
Display of flight's planned path on the selected radar window upon assumption of control.
Display of geographical position of the cursor on the selected display.
Range and bearing line control.
Brightness control.
Range selection.
Range ring manipulation.
Centre selection.
Synthetic track presentation.

The level filter is changeable between label and also track filtering.
The operator is able to select the displayed tracks, i.e.: which are outside or between the height limits. Those flights which are expected to enter the sector are not filtered.
Label format selection
The operator is able to select the number of history dots, the label orientation and the text size.
Automatic label conflict avoidance is not planned, however the operator is able to select an "autolabel" function, when the label orientation is dependent on the track course.
Radar service selection

Track labels
The track labels are selectable separately for each radar display: They can be of Standard and Reduced size.
The label consists of max. 5, and minimum 2 lines.
Different label content has been defined for uncorrelated and correlated tracks and the content of correlated tracks depends on the operator's role.
Empty lines and empty fields are not displayed (justified to the left),
The non-concerned or uncorrelated, concerned, advance warning and assumed flights are displayed in different colours.
As a general rule, the Action mouse button shall be used for data input, and the Information button is used if information is required for a flight.

Input is made via invoking menus and scrolled lists:

Callsign Menu:
Selecting the aircraft identification field with the Action button, a Callsign Menu is invoked, which allows the input various orders, e.g: assume, transfer, request release, release, skip, proceed direct (including elastic vector), close flight plan, hold/terminate hold, proceed to ALTN aerodrome, conformance check off, MTCA area alert off,
RBIW off. The displayed and selectable pushbuttons are depending on the flight's state (not yet assumed, assumed), and on the operator's role.
In order to reduce the length of the Callsign Menu, two states are available:
basic, containing the most often used functions and the
extended, which contains all functions.

Scrolled lists invoked from the track label and flight list windows
The following scrolled lists are invoked by clicking on certain fields:
Sector Scrolled List, Level Scrolled List, Assigned Rate Scrolled List, Assigned Speed Scrolled List, Assigned Heading Scrolled List, Waypoint Scrolled List.

The correct sizing of these pop-up windows is very important. The selection shall be easy, data shall be readable, however the size of the

window should be small that only the smallest area is covered on the radar screen. To reduce the necessary cursor movement the correct default position of the cursor is important when the pop-up window is invoked.
To avoid incorrect data entry these pop-up windows also contain the callsign of the aircraft whose label the scrolled list was invoked.

Track information
The following information can be initiated to be displayed for a selected flight on the radar display:
Flight leg with or without conflicts,
Extended Label Window (which contains the full details of the selected aircraft with estimate data for the next route points),
Next sector's frequency, and the Vertical Profile,

Special windows on the radar screen
In addition to the flight list windows, the radar window can also display:
Coastlist Window, which contains those assumed or concerned flights, which are coasted from the display or for which the operator suppressed the display of data label.
Stack Window, containing data of holding aircraft.
Correlation Window, which is invoked when the operator wants to correlate a track manually.

Flight list windows
Due to stripless operation a sophisticated flight list window system has been developed. Dedicated memoir fields are also provided for the operator.

The operator is able to manipulate data via track labels and also via list fields. Same functions are available via flight list fields as via track labels. In addition there are certain functions, which can be input via flight lists only, e.g. start-up and departure input, inbound estimate data modification, etc.

In order to reduce the size of the lists, most lists are available in basic and in extended format.

The content of the lists are role dependent. Some windows contain two lists, e.g. the Start-up Window, where the lower part contains those aircraft which are expected to request start-up clearance, and the upper part contains those which have already done so.

Special call sign menus have been developed. The selectable functions of the callsign menu invoked by clicking on the call sign depends on the window, or if the contains two list, it depends on the list.
E.g.: If the Aerodrome Controller selects a flight from the Landing List of his Sector Window, the invoking Callsign Menu enables him to input ARRIVED or MISSED APPROACH information.
If he selects a flight from the Transit List of the same window the invoking Callsign Menu enables him to input TRANSFER, CLEARED FOR APPROACH, RELEASE and CLOSE FLIGHT PLAN information.

The following flight list windows are planned:
Start-up Window, for manipulation of flight data of aircraft starting up the engines at Ferihegy aerodrome (for GND controller use)
Taxi Window. It is planned to display and to provide the facility of aircraft taxiing at Ferihegy aerodrome. It is also planned for the GND controller.
Take-off Window. It is used by the Aerodrome Controller and contains those flights which are waiting for take-off clearance.
Inbound Window. It contains the data of those aircraft which are expected to enter the sector.
Sector Window. It is planned to provide the facility to display and manipulate data of aircraft currently under the control of the sector.
Departure Window. It is used by the APP,ACC, MIL and FIC sectors and contains the data of those aircraft which are departing from the sector area.

As an example, the Military sector has the following flight list windows:
Departure Window. It contains the data of OAT flights (fully OAT or mixed OAT-GAT which operate as OAT in the first part of the flight), departing from domestic military aerodromes.
The Pending List of the window displays the aircraft expected to start-up the engines within VSP time (30 min).
The Active List contains the data of aircraft for which start-up information has been input. Dedicated fields are available for the military operator to input free-text departure route information and clearance data (which has been coordinated verbally with the relevant civil sector).
Inbound Window. It contains the data of those full OAT or mixed OAT/GAT flights for which the military controller made the departure input and those GAT/OAT flights, which are expected to be controlled by the military sector, but currently controlled by a civil sector.
Sector Window. It contains the data of those military OAT flights which are currently controlled by the military sector.

Capability is provided to (only) view the departure and sector list of the military sector by the civil sectors.

The lists normally contain the usual flight plan elements, e.g. Callsign, type, estimate data, etc. but some special fields are also included, e.g. the tower controllers are able to indicate ATC en-route clearance delivery, the MIL ,and FIC controllers can input coordinated level and route information for the flight.

FDP windows
The FDP windows, which can accessed via a dedicated FDP bar provide capabilities to manipulate basic flight plan data, input estimate and position report data and displays outbound estimate data to be forwarded verbally to adjacent units by the FD staff.
(It should be noted, that in MATIAS the estimates are received and forwarded by the FD section, modifications and cancellations are received and forwarded by the relevant sectors.)
Functionality is also provided for displaying load count information.

The following FPL windows are available:
FPL Window, which allows the operator to view and manipulate flight plan data. It also provides the capability for the control staff to initiate sending of FPL, ARR, DEP and RQS messages via AFTN.
EST Window, which allows the operator to input estimate data without or together with FPL data (e.g. AFIL)
Route Data Window (for FIC). It provides the facility to enter estimates, position reports and reporting requirements.
Flight Inputs Log Window. It provides the facility to view all flight data related inputs that have been applied to a selected flight record.
The *Workload Estimate Window* informs the operator about the expected workload based on FPLs in the system.
The operators can manipulate RPL data via an *RPL List Window*.
Dedicated role is able to process bulk RPL data received from IFPS.
A special *Outbound List Window* is provided for the FD staff which contains those data that has to be forwarded verbally to adjacent foreign units or to other domestic units.

Coordination window
A Coordination Window is planned to support:
- silent coordination conversations relating to flight transfer data between MATIAS sector controllers,
- verbal coordination with neighboring units (REV and EST CNL messages) . The operator is able to indicate the acknowledgment of the forwarded message by the receiving unit.

This window should display also the operational content of the received REV or MAC messages

should the MATIAS not be able to process these OLDI messages automatically.

When the system detects that after data modification coordination is required between two sectors within the MATIAS, it does not process the change, but, instead, initiates a silent coordination conversation between the sectors concerned.

The coordination messages are predefined and made of structured fields. By selecting different fields, the receiving controller can accept, refuse the modification or he can make a counter proposal.

The window is not planned to be used for ATS route crossing requests between the military and the civil sectors due to the density of ATS routes in the FIR. Verbal coordination is planned between the civil and military sectors. The result of this coordination can be inserted into dedicated fields in the flight lists.
The civil sectors are able to view the military flight lists, flight plans and flight tracks.

The Coordination Window is split into two parts, i.e. messages received - "IN List", and messages to be sent "OUT List".

Two Coordination Windows are planned for a sector, one for the Executive and one for the Planning Controller, with the same content.

Conflict windows
Due to stripless operation, Medium Term Conflict Analysis and alert generation is a very important feature of the MATIAS.
The result of MTCA can be displayed on the radar screen and in two dedicated conflict windows.

The operator is planned to be able to request the system to display the flight path of a selected flight and the conflicting traffic on the radar picture in a horizontal plane.

An ODID-like Conflict and Risk Display provides a dynamic display of all predicted medium term conflicts and/or risks including intrusion into reserved areas.

A static Vertical Aid Window is also provided for the operator, which displays the vertical profile of a selected flight.

The operators are able to exempt selected flights from MTCA.

The Planning Controller is also able to indicate those conflicts which should be solved by the Executive Controller.

AIS (or Information System) windows
The AIS windows contain all important information, which are required by the operators in order to provide efficient air traffic services to aircraft.
The AIS system can be accessed by a dedicated AIS bar.

Data input is made by selected role(s). An AIS Operator is responsible for data input.

The following functions are available :
The operator is able to view various meteorological data, including:

- Sensored current met data at Ferihegy aerodrome, like wind, visibility, RVR, QNH, e.t.c,
- METARs, TAF, SNOTAMs etc. for selected aerodromes or for a selected group of aerodromes,
- Upper wind and temperature data,
- General Aviation Forecast data,
- Weather picture received from meteorological satellite

NOTAMs in force. It should be noted, that MET and NOTAM messages will also be displayed in decoded format.

Dedicated windows are available for displaying equipment status, like VORs, RADARs, ILS, etc.

The user is able to select an aerodrome and view all information (met, equipment, services, opening hours, etc.) relevant to the aerodrome.

The operator is also able to select hotspots on his radar picture. Selecting the hotspot, information is presented in a dedicated window for the selected aerodrome, navaid or area.

A very important data is the frequencies currently in use by the ATS units. This data is displayed in a dedicated window for the controllers. Supervisory roles are able to manipulate data within this window. It should be noted, that the next sectors frequency is also displayed in the target data label.

Dedicated windows are planned for displaying current and planned activity data of danger, restricted and military areas and other special airspaces. Supervisory positions are able to modify data as required. Data in these windows control the automatic display of the relevant radar maps at the sector positions. Functionality is provided for the AIS Operator role to create an ad-hoc restricted area and input planned activity data.

The operator is able view various maps, e.g. sector map, aerodrome maps, aeronautical chart, etc.

In addition document pages can also be presented, e.g. AIP pages, Letter of Agreements, administrative regulations, shift schedule, etc.
All these information are presented in a so-called Information Window.

The AIS Operator is able to generate and send predefined bulletins (met. data and NOTAMs) to various addressees.

The TWR controllers are able to input and display in dedicated windows the maintenance cars and vehicles operating on the runways and taxiways.

Sectorisation windows
Dedicated windows are available for the Operational Supervisor to initiate sectorization changes and to move a role from a faulty hardware to an other equipment. A separate window is planned for reallocation of flight data roles between the available workstations.

Communication windows
Communication windows are provided for the COM Operator role to supervise and control the messages exchanged via AFTN, OLDI and MET connections.

An AFTN Message Window is provided for displaying, addressing and sending external AFTN messages. It should be noted, that all outgoing AFTN messages are planned to be displayed at the COM Operator, who is responsible for the correct addressing of the messages.

A dedicated window is provided for AFTN link control. The operator is able to select AFTN channel mode, e.g. Operational, Off-line and he is also able to set message sequence numbers. He is able to view all received or sent AFTN, OLDI and MET messages via a Log Window.

In the case an unrecognizable message is received by the system, he is alerted, he can correct the message if it is corrupt, route the message to other roles (e.g. free-text AFTN message), or he can discard it. He is also able to repeat transmission of AFTN messages, or can request repetition of a previous message and generate SVC messages.

Plans and Prospectives for Research and Development in Air Traffic Management

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SUMMARY

In 1993, the U.S. Congress passed the Government Performance and Results Act (GPRA). The purpose of the legislation is to improve Federal program effectiveness and public accountability by promoting a focus on results, service quality and customer satisfaction. The GPRA shifts the focus of program accountability from agency internal activities to the products and services planned to be placed in the hands of external customers and the eventual benefits to be achieved as a result. Decisions regarding expenditures of public funds will be justified in terms of these products, services and benefits. This perspective is very useful in planning and prioritizing research and development (R&D) projects in air traffic management (ATM). In particular, it would be useful to establish a comprehensive framework of performance goals to guide R&D investments in ATM. Some progress toward this end has been achieved at the Federal Aviation Administration (FAA).

LIST OF ACRONYMS

ADS-B	automatic dependent surveillance - broadcast
AGL	above ground level
ATM	air traffic management
FAA	Federal Aviation Administration
GPRA	Government Performance and Results Act
R&D	research and development

1. INTRODUCTION

Fig 1 illustrates the central notion of the GPRA as applied to the FAA R&D program in ATM. The GPRA focuses on outputs, external customers and outcomes. An output is a product or service produced by the FAA and delivered to its customer community. An outcome is the result, consequence or benefit achieved by placing the output in the hands of the customer. For example, an intended outcome of an R&D initiative might be to reduce the frequency of runway incursions. The output that the initiative is pursuing might be a new surface surveillance capability based on the automatic dependent surveillance - broadcast (ADS-B) technique. (ADS-B is a function that automatically broadcasts, via a data link, aircraft position data derived from the on-board navigation system.)

The R&D program and its various activities and products (for example, system analyses, simulation experiments, field trials and technical reports) contribute to agency outputs but they are not especially helpful for understanding the potential value of R&D investments. Government decision makers allocating scarce funding resources are concerned with outputs to be delivered and outcomes to be achieved.

2. CUSTOMERS AND STAKEHOLDERS

The GPRA philosophy is very particular about the notion of customers. GPRA customers exclusively are the end users of the agency's products and services. FAA's customers include passengers traveling in commercial aircraft, users of air cargo services and commercial, private and military aircraft operators.

A sharp focus on the end customer forces one to think about the ultimate outcomes achieved by agency outputs as opposed to considering consequences experienced by intermediaries. For example, if one views tower controllers as the customers for an improved airport surface surveillance capability, it would be possible to develop and implement a new system that is well received by the controllers but not effective in providing an intended reduction in incursions. The controllers are essential partners in any effort to reduce incursions and any surface surveillance capability developed would need to meet their approval. But the focus of the R&D investment and the associated implementation expenses must be the intended improvement in the safety of aircraft operations on the surface as experienced by passengers and aircraft operators.

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

The focus on outcomes for end customers also fosters a more comprehensive approach to R&D program planning and management. Delivering benefits (outcomes) to the customers of the ATM system often requires both technical improvements and changes in procedures and rules. In R&D, it is easy to overlook the procedural aspects and focus only on technical innovations. The GPRA focus on benefits derived by end customers requires coordinated delivery of all essential elements of system improvements.

Stakeholders are important as well. A stakeholder is a party concerned with the outcomes achieved but not involved as an end customer of FAA's outputs. The air transportation system dramatically effects the national economy and virtually everyone therefore can be seen as a stakeholder. More specifically, U.S. government agencies and legislative bodies concerned with the safety and efficiency of air transportation are principal stakeholders in FAA's R&D program as are state and local governments, the international aviation community, aviation associations, commercial pilots, FAA's operational staff, aircraft and equipment manufacturers, universities and the research community.

The objective of the GPRA is to assure that value is delivered to the agency's customers. It follows that customers should be involved in agency planning activities and that program design should be conducted in collaboration with the customer community. The stakeholders need to be involved as well.

3. PERFORMANCE GOALS

The GPRA is not satisfied with qualitative outputs and outcomes. Rather, it requires that intended outputs and outcomes are expressed as quantitative performance goals, that is, target levels of performance expressed as tangible, measurable, objectives against which actual performance can be compared, including goals expressed as quantitative standards, values or rates.

For the example of the preceding section, the intended outcome could be expressed properly as follows:

> By 2003, reduce the frequency of runway incursions by 30 percent relative to the 1996 baseline.
> - The frequency of incursions is the number of incursions divided by the number of aircraft takeoffs and landings.
> - A runway incursion is an incident in which an aircraft, vehicle or other object creates a collision hazard for an aircraft on an active runway.

A correctly stated output for this outcome could be the following:

> By 2002, develop and implement an airport surface surveillance capability based on ADS-B meeting the following performance goals:
> - Statement of quantitative technical goals associated with target detection and identification, false detections, update rate, and all-weather capability.
> - Statement of quantitative goals for capital and life cycle costs

The basic precepts of the GPRA are easy to appreciate. Like any business, government's function should be to provide products and services to customers who, in turn, derive benefits that justify the associated expenses. Quantitative performance goals are essential to understanding whether or not proposed investments are likely to be cost beneficial.

4. APPLICATION TO R&D

Difficulties can arise in applying the GPRA to R&D projects. The principal problem is that the benefits of R&D are often uncertain. The example used in the preceding section asserts that a specified surface surveillance capability will achieve a 30 percent reduction in the frequency of runway incursions by 2003. Presumably, past research justifies the assertion.

Suppose that little research has been conducted on the subject. How does one get started? The objective is still to reduce the frequency of runway incursions. But what quantitative outcome should be used and what outputs can be identified? The dilemma that arises is the requirement for a goal before the research to establish a viable goal has been conducted.

The solution can be to frame the initial research activity around investigating the problem, identifying and analyzing potential solutions and their benefit-costs, and establishing performance goals for outcomes and outputs. The output of the first phase of research is then an improved understanding of the problem and its potential solutions. One publishes a technical report that provides a

basis for dialogue with the customer community prior to making a substantial R&D investment in pursuit of solutions. Through this process, GPRA imposes a healthy discipline on the R&D process. One is required to think clearly about the alternatives for solving the problem prior to committing significant resources to any of them.

This discussion illustrates an important point to be made about performance goals. In particular, the development of viable goals is a significant task in itself. In the ATM area, one will need to understand both the operational issues and the technological opportunities for achieving system improvements. Alternative approaches must be analyzed and their likely benefits and costs compared. Finally, one will want to collaborate with the customers and stakeholders involved prior to expending significant resources.

5. ESSENTIAL ELEMENTS OF R&D PROGRAM MANAGEMENT

It has been said that quality research is a matter of doing good work, doing it well and publishing the results. Pragmatically, in the field of ATM, it is a matter of understanding what needs to be done, developing a sound plan for doing it, collaborating with customers and stakeholders in these planning activities, and then efficiently accomplishing the project plan. A more specific list of essential elements of R&D program management is the following:

- Establish clear outcomes with their associated performance goals
- Analyze alternatives for achieving the outcomes
- Identify clear outputs with their associated performance goals
- Develop a reliable plan for producing the outputs
- Develop a benefit-cost understanding of the selected course of action
- Collaborate with customers and stakeholders on the selected course of action
- Establish productive partnerships with industry, academia, government agencies and the international aviation community to foster R&D contributions from these sectors and to involve them in the development process.

There are, of course, interactions among these elements and they are developed iteratively over time.

6. OUTCOMES FOR ATM SYSTEM DEVELOPMENT

The FAA research and development program in ATM is focused on seven principal outcomes that represent value to the end customers of the system:

- *Increase system safety*, that is, reduce the risk and consequences of accidents and incidents in the ATM system.
- *Decrease system delays* so that the time interval over which a flight occurs corresponds to the interval preferred by the user.
- *Increase system flexibility* by more frequently allowing users to operate at the altitudes and speeds and on the routes they prefer.
- *Increase system predictability* so that, even when delays are necessary and flexibility is limited due to traffic congestion or other factors, the ATM system can reliably estimate when aircraft will be able to depart and when they will arrive at their destinations. Predictability is an important service attribute for airlines in managing their fleets over the day.
- *Increase user access* to airports and airspace in all weather conditions.
- *Maintain a high level of equipment and service availability* to assure uninterrupted ATM operations.
- *Increase the productivity of ATM services* as a means for controlling costs as demand increases.

One might add other outcomes to this list, including an objective to reduce the environmental consequences of aircraft operations, in particular, the impact of noise on communities within major terminal areas. Even so, the outcomes listed provide a useful starting point for structuring an R&D program and its framework of performance goals.

7. A HYPOTHETICAL EXAMPLE

- The following hypothetical example illustrates how one might structure R&D projects around the outcome concerned with increasing system safety. The hypothesis is that an informed group of researchers, analysts and operational specialists, in considering means for improving the safety of ATM operations, has collected and analyzed the necessary data and determined that there are four principal opportunities relevant to R&D, in particular (Fig 2):

- Reduce approach and landing accidents and incidents
- Reduce weather-related accidents
- Reduce the frequency and consequences of runway incursions
- Reduce the frequency of accidents and incidents related to human factors

Further detailed analysis of each of these four areas yields the following performance goals and outputs:

- *Approach and landing:* By 2003, reduce the frequency of approach and landing accidents by 35 percent relative to the 1996 baseline by producing the following output:
    - Establish satellite-based Category I precision approach capability at all runway ends at public use airports.
- *Weather:* By 2003, reduce the frequency of weather-related accidents by 40 percent relative to the 1996 baseline by producing the following outputs:
    - Implement specified weather products on government and commercial weather platforms
    - Provide data link communications to transmit warnings of hazardous weather to aircraft operating in major terminal areas and in en route airspace above 6,000 feet (1830 meters) AGL.
- *Runway incursions:* By 2003, reduce the frequency of runway incursions by 50 percent relative to the 1996 baseline by producing the following outputs:
    - Implement specified improvements in runway lighting, marking and signs and in surface navigation, surveillance and communications capabilities
    - Implement decision support systems for taxi routing and conformance monitoring and for surface conflict alert.
- *Human factors:* By 2003, reduce the frequency of human-factors related accidents by 35 percent relative to the 1996 baseline by producing the following outputs:
    - Implement improved programs for pilot and controller selection and training
    - Implement means for monitoring human performance
    - Implement guidelines for the design and validation of automation systems to assure better that they reliably perform their intended functions in the operational environment.

It is further hypothesized that an analysis of accident statistics and the expected characteristics of the future air transportation system leads our analysts to the conclusion that achieving the four performance goals above will reduce the frequency of accidents by 30 percent. The Level 1 performance goal becomes:

- By 2003, reduce the frequency of accidents associated with ATM operations by 30 percent relative to the 1996 baseline.

The result of the analysis is a two-level framework of performance goals (Fig 2) which clearly could be further developed to lower levels. An assessment of the relative benefits and costs associated with the individual goals and outputs would provide a basis for prioritizing R&D investments among them.

A similar analysis of alternative means for progressing the six remaining outcomes of Section 6 above would produce a comprehensive, rational framework for investment decision making in ATM R&D.

Some will find the hypothetical example described above too elaborate. Several specialists could work for a year or more to collect and analyze the data needed to identify alternative opportunities for increasing system safety and to estimate their associated benefits and costs. Expenses amounting to several hundred thousand dollars (U.S.) could accrue before a clear picture emerged of the appropriate program. Some would argue that this investment is not an effective use of funds. The other side of the argument, of course, is that significant resources are expended in ATM R&D and one cannot be confident that they are well applied without the sort of analysis described. In addition, one cannot demonstrate to oneself or to others the value of the proposed investments without the results of this work.

It is prudent to apply a certain percentage of the resources devoted to ATM R&D to systematic program planning, including the analysis of needs and opportunities for addressing those needs together with the establishment and maintenance of an appropriate framework of R&D performance goals. The art is in balancing the resources devoted to planning and goal setting with the resources dedicated to developing the solutions. In any case, planning and execution must proceed in parallel. The planning is not finished until the program is completed.

8. OTHER ADVANTAGES

A framework of performance goals for ATM R&D has advantages beyond the ability to improve investment decision making. In particular:

- Consideration of alternative means for achieving goals broadens one's perspective to include potential solutions that might not have been considered otherwise. One focuses on goals and then solutions rather than approaching R&D with the painstaking development of technological "solutions" which many times are then left to seek out corresponding "problems" to be solved.
- Established goals provide an objective means for assessing program progress. They also provide "exit criteria." When the goal is achieved, work should stop.
- Goals provide a nearly universal means for explaining one's work, both to oneself and to others. They are essential for convincing the Board of Directors, whomever they may be, of the value of R&D investments.
- Clear goals focus the energy of the research team on the desired end result. Frequently, this focus is more effective than elaborate program plans with their many milestone charts and descriptions of future research activities.

9. CONCLUSION

It is intended that R&D planning at the Federal Aviation Administration increasingly will be based on a comprehensive framework of objective performance goals describing what is to be achieved and by when. The framework will be used in making investment decisions and will provide a principal means for communicating program objectives and priorities to agency customers and stakeholders.

The benefits of this approach will be an R&D program that can be shown to be well focused on the needs of the agency's customers and that is well understood by the FAA's customer and stakeholder communities

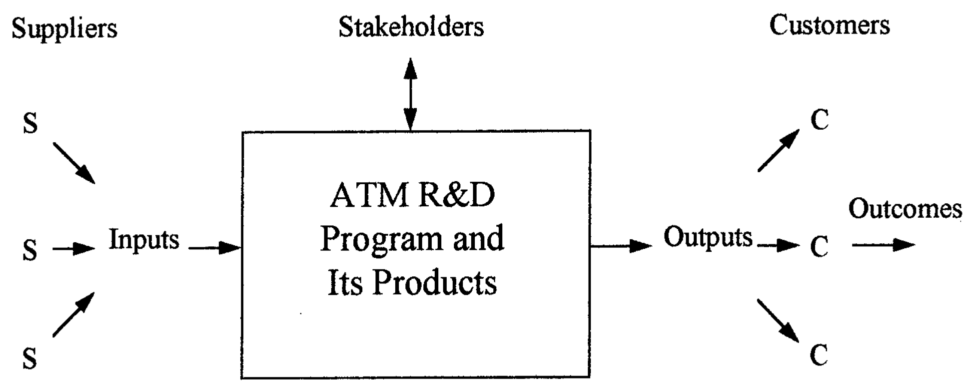

Figure 1. GPRA View of Agency Accountability for Results

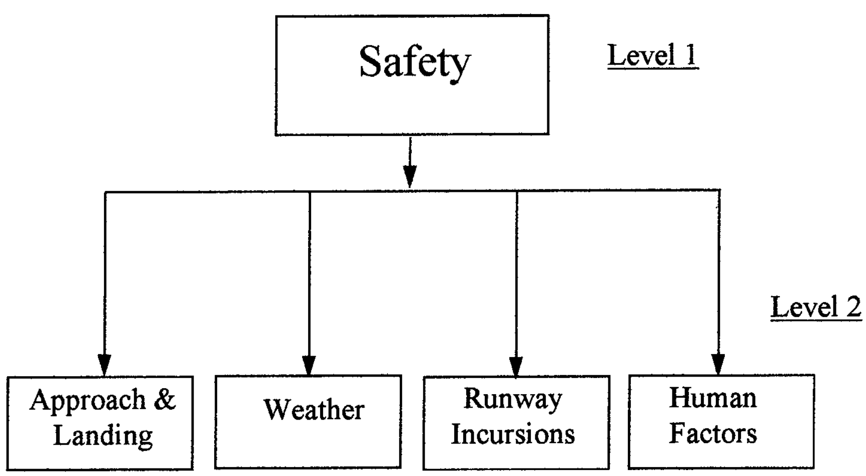

Figure 2. Performance Goals for System Safety

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Plans and Prospectives for Research and Development in Air Traffic Management

Clyde A. Miller

29 May 1997

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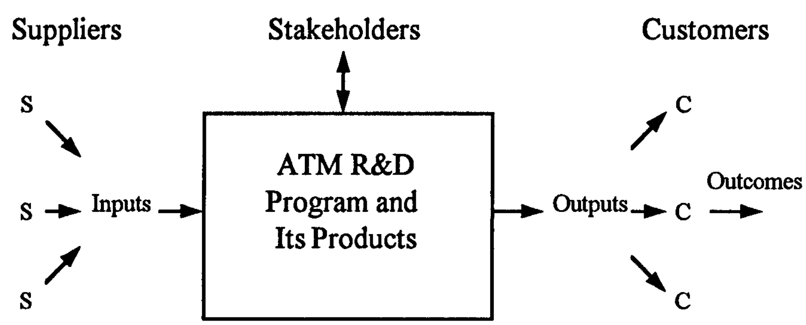
GPRA View of Agency Accountability for Results



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Outputs and Outcomes

- Outputs:
  - Products and services produced by the agency and delivered to the agency's customer community
- Outcomes:
  - Consequences and benefits achieved by customers

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Customers and Stakeholders

- Customers - EXTERNAL:
  - Passengers
  - Private aircraft operators
- Stakeholders - Involved, not customers:
  - FAA's operational staff
  - Commercial pilots
  - Aircraft and equipment manufacturers
  - International aviation community

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Performance Goals

- Target levels of effectiveness
  - Effectiveness is the extent to which the purpose is achieved
- Tangible, measurable and objective
- Outcomes and outputs should be stated as performance goals

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Example of an Outcome

- By 2003, reduce the frequency of runway incursions by 30% relative to the 1996 baseline
  - The frequency of incursions is the annual number of incursions divided by the number of aircraft takeoffs and landings
  - A runway incursion is an incident in which an aircraft, vehicle or other object creates a collision hazard for an aircraft on an active runway

Example of an Output

❖ By 2002, implement an airport surveillance capability based on ADS-B meeting the following performance goals:

- Probability of detection and identification.....
- False detection and identification rate......
- Airport coverage requirement............
- Update rate....................................
- Capital and life cycle costs.......

Goals Are Hard Work!

❖ Operational analysis

❖ Technology assessment

❖ Cost-effectiveness and cost-benefit studies

❖ Collaboration with:

- Customers and stakeholders
- Subject-matter experts
- R&D partners
- Industry

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Essential Elements of R,E&D Program Management

- Clear outcomes with performance goals
- Analysis of alternatives for achieving the outcomes
- Clear outputs with performance goals
- Reliable plan for producing the outputs
- Cost-benefit understanding of the selected course of action
- Customer and stakeholder involvement
- Partnerships with industry, academia, other government agencies and international community

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FAA Initiative

- Structure the R&D program in air traffic management around specific:
  - Outcomes
  - Outputs
  - Performance goals

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Outcomes for ATM

- Increase system safety
- Decrease system delays
- Increase system flexibility
- Increase system predictability
- Increase user access
- Maintain infrastructure service and equipment availability rates
- Increase productivity in system operation and maintenance

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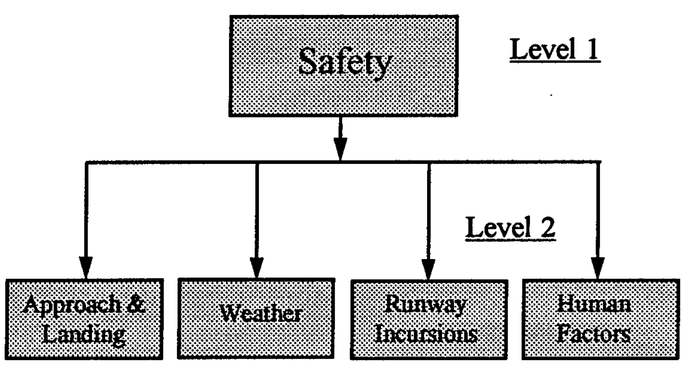
System Safety



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Level 2 Goals for System Safety

- Approach and Landing: By 2003, reduce the frequency of approach and landing accidents by 30% relative to the 1996 baseline
  - Output:
    - Provide satellite-based Category I approach capability for all runway ends at public use airports
- Weather: By 2003, reduce the frequency of weather-related accidents by 40% relative to the 1996 baseline
  - Outputs:
    - Specific aviation weather products implemented on government and commercial weather platforms
    - Air-ground data link to provide weather products to the cockpit

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Level 2 Goals for System Safety

- Runway Incursions: By 2003, reduce the frequency of runway incursions by 50 % relative to the 1996 baseline
  - Outputs:
    - Signing, marking and lighting improvements
    - Surface navigation and surveillance improvements
    - Decision support for taxi routing and surface conflict alert
- Human Factors: By 2003, reduce the frequency of human-factors related accidents and operational errors by 30% relative to the 1996 baseline
  - Outputs:
    - Selection and training techniques
    - Techniques for monitoring human performance
    - Guidelines for design and validation of automation systems

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System Safety Level 1 Performance Goal

- By 2003, reduce the frequency of accidents associated with air traffic management operations by 30% relative to the 1996 baseline

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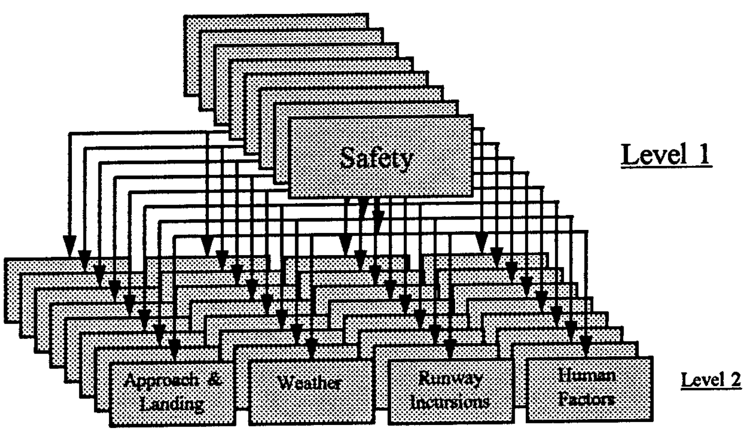
ATM Goals Framework



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Advantages of a Performance Goals Framework for ATM R&D

- ❖ Requires consideration of alternative means (outputs) for achieving outcomes
- ❖ Provides a basis for prioritizing investments
- ❖ Provides a means for assessing progress
  - Provides project exit criteria
- ❖ Answers the question, "Why are we doing this?"

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Conclusions

- ❖ FAA R&D program in ATM increasingly will be based on performance goals
- ❖ The goals framework will:
  - Support investment decision making
  - Facilitate communications with customers and stakeholders
- ❖ Benefits will include a better understood and supported R&D program

AGARD01.PPT 18

CNS/ATM Concept
ICAO Prospective

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Background review

In 1983, ICAO founded the FANS Committee (Future Air Navigation System) to trigger a global reflexion on the radioelectric means to be used by Civil Aviation in 2000 and further.

In dense areas (like the European « core area » between London, Paris, Milan, Berlin and Amsterdam) the growth of traffic will no more be manageable by the current control methods ie multiplying the number of sectors more and more. En-route and airport delays generate time and financial losses.

In oceanic and desertic areas the traffic is low and will remain low for a long time.

The lack of communication and navigation means generates large lateral and longitudinal separations which sometimes do not avoid near misses over continental crosspoints.

There was a need for more reliable but affordable controller-to-controller and controller-to-pilot links associated with modern and reliable navigation aids.

Paradoxes in modernity

Aviation is generally famous for technical modernity but the International Maritime Organization was the first to implement a satellite communication system designed between 1976 and 1979 and put into operation on 01/02/1982.

It was then possible to maritime crew and travellers to phone everywhere in the world, when aircraft pilots were unable to have a confortable contact with ATC.

General trends of FANS Committee report

In its 1993 World wide transition plan; FANS 4 produced trends and not recommandations, nor imperative plannings.

With due apologies to the conceptors, a very brief digest of the report can be read now as : introduction of CNS/ATM concept.

- In the communication field, encourage satellite use rather than HF and digital exchanges when possible, rather than analog voice communications.
- In the navigation field encourage satellite (GNSS) means associated with a new regulatory concept « required navigation performances ».

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

- In the surveillance field definition of a new technique *« Automatic Dependent Surveillance »* ADS in areas not covered by radar and upgrade radar surveillance by enhanced secondary (mode S) radar. This ADS concept was further called ADS contract.

  Please note that the FANS Committee did not imagine at that stage ADS Boadcast, or Free flight which generate now many ideas and technical proposals.

- For obtaining benefits in ATM of these CNS proposals increasing use of automation was a major hope :

  - ATM automation — will make it possible to formulate real time flow management strategies,

    will allow negociation between ATC and aircraft to enhance tactical control.

  - Datalink and voice channels combined with automation aids will be used for aircraft not capable of automated negociation.

  - Flexible oceanic ATM will accomodate user-prefered trajectories.

  - Both flow management and tactictal control will be enhanced for en-route and terminal operations.

  - Traffic will flow smoothly into and out of terminal areas.

  - New ATM systems will support increased airport capacity.

Aside these technical efforts and their investments, the report aimed at operational benefits : reducing delays, accommodating user-prefered trajectories and flexible routing, reducing the communicator's workload and channel congestion etc.

Degree of implementation of the transition plan

Two chapters of the FANS 4 report are attached : « *Global planning* » and « *System Implementation* ». Let us have a look on the beginning of operational use of the three CNS composents.

- Communication

The AMSS was installed on more than 110 aircraft, rather for passengers public telephone than for ATC needs. In case of emergency, pilots could dial the telephon number of an ACC, but it never occured !

Nevertheless AMSS is currently used for digital controler to pilot data link (CPDLC) over Pacific using a non standard application procedure called FANS 1 (initiated by Boeing on the B 747-400) or FANS A (Airbus).

This procedure has not yet really allowed dynamic negociation of flying routes.

A reduction of lateral or longitudinal separations is under study but leads to certification problems due to the performances of the network.

Among the 1500 aircraft foreseen to be AMSS equipped some hundreds are equipped/ordered with the FANS 1/A equipment. As an example all B777 are basically equipped and Singapour Airlines ordered its 17 A340 to be equipped.

Nothing is foreseen up to date for North Atlantic as it is doubtfull that interim FANS COM could introduce operational benefits as reduction of separations. Furthermore the present reduction of vertical separations obtains more benefits on the short term.

The unique VHF datalink currently operationnal is the Airlines'ACARS but VDL 2 (with higher speed and ATN compatible) is ready to start. VDL 3 (digital mix of voice and data) is postponed by FAA.

Furthermore a forth VDL is proposed by several experts. Some european Airlines gained European Commission DG 7 funding for experiments on VDL 4.

The risk is to have different regional implementations.

The secondary surveillance radar Mode S is quoted twice in the FANS 4 report : for communication and surveillance. Two degrees of performance can be achieved but were not precised on the chart :

a) Enhanced surveillance (selective addressing + downlink aircraft parameters)

b) Two way datalink wich is a genuine communication application.

   This application is not implemented to date in North America (NAM Region). Eurocontrol is supporting it more warmly than the FAA, but the POEMS program (pre-operational european Mode S) is starting now with enhanced surveillance capability only.

The FANS report announced initial implementation of ATN in NAM/NAT/EUR around 1995.

There is a misunderstrunding on the word ATN. In this document, it meant « Network and Transport services ».

When you read now in the Press (like ATC News) « ATN versus FANS 1 » it means air-ground applications.

ATN covers a wide field from lower OSI layers, by upper-layers, to application layers called CNS/ATM 1.

The network and transport layers are ready and some ground-ground applications will start soon (1998).

There are still discussions on air-ground applications. The standards are ready (and more efficient than FANS 1 application) but are different from FANS 1/A which was implemented first.

- Navigation

GNSS was foreseen for en-route operational use in 1993-95 in ASIA/PAC and it really happened (in practical GPS only is used).

The FANS 4 report did not mention the augmentation systems (WAAS, EGNOS, MTSAT) which appear to be necessary for the Terminal areas (at least the most congested). The middle term (1996-2000) forecast of the committe seems to be postponed to 2000-2010.

Transition from ILS to MLS should have been precised in the '95 MLS meeting and was not : many states hope to avoid implementation of the MLS, waiting precision approaohes with GNSS (including local area augmentation system).

Surveillance

ADS (contract) was foreseen in 1993-95 in ASIA/PAC.

As explained above an interim FANS communication system was implemented over the Pacific in 1996. It includes only controller to pilot data link (CPDLC) but the forecast of the FANS Committee stays pretty good : CPDLC includes a "triggered dependant Surveillance". When contacting the ATC, the pilot sends its parameters in the same message.

FANS/1/A avionics has ADS capability. It needs :

- finalization on board,
- implementation on ground system.

Operational use is now foreseen at the end of 1998.

There is some pressure from airlines to extand the FANS/1/A interim protocols and applications to Africa, Indian ocean, Siberia, Iran and Pakistan. If that happens, it will probably be CPDLC rather than ADS.

The inadequacy of FANS/1/A protocols and avionics to obtain operational benefits on more congested areas should lead to CNS/ATM 1 solutions.

"ADS Europe" is an experimentation which started in 1996 and is still living. It involved dedicated aircrafts of several european airlines (British Airways, KLM, Lufthansa, Air France) on routes from North Atlantic to Asia.

The technical results are considered as positive. The operational implementation, mainly on North Atlantic, is still on debate.

ADS Broadcast is a new concept, not proposed by the Committee.

Each equipped aircraft would broadcast its position (altitude, heading, etc. associated with time).

The neighbouring aircrafts (with adequate reception, processing and display) will have a situation awareness allowing separation insurance.

Two techniques are proposed to fullfill this operational need :

- the "long squitter" of the SSR transponder;

- the Self organized time division multiplex (in the vhf band) also called VDL 4.

The long squitter is favoured by the FAA, the STDMA by the swedish Luftvartverket and some german experts. The competition between these two systems is not clear.

NOTE

ADS contract, ADS broadcast and CPDLC are studied by the same ICAO body (ADS panel).

The SSR Mode S was foreseen in the 1993-95 term in the NAM region. As explained before, the FAA no more favours the Mode S as two way data link.

Even restricted to enhanced surveillance, Mode S would facilitate radar tracking and controller task by downlinking some aircraft parameters (like heading, speed, etc.).

the FANS 4 report did not mention ACAS (Airborne collision avoidance system) based on the SSR transponder. ACAS and some of its implementations (TCAS 2 etc.) were known bud considered out of pure surveillance systems.

CONCLUSION

Four years later, the FANS 4 global planning appears delayed but globally valid. The principal lack in the report is probably the absence of reflexion on the FANS 1 solution which was designed by Boeing at the same time (but rather secretly).

This leads to new paradoxes, Pilot and controller have interim but modern communications techniques on huge areas with low traffic (to day Pacific ocean, and may be tomorrow Indian ocean).

Over the Atlantic ocean they don't have.

Large and cosfull experiments are running for more congested areas (ADS Europe, EOLIA).

ADS Europe did not engage pilots, because they were transparent to automatic position reports . EOLIA will demonstrate and evaluate data link services in an operational-like environnement (using ATN communications infrastructure).

Taking profit of data link techniques needs to make implementation not only on the ground working stations or airborne avionics, but also in the controller and pilot working methods.

It leads to delicate certification problems and huge investments which explain the prudence of the operators.

ACRONYMS

ACARS	Aircraft communication and reporting system : Network using VHF or INMARSAT (AMSS)
ANC	Air navigation commission (ICAO)
ATM	Air traffic management
ATN	Aeronautical telecommunications network
ADS	Automatic dépendant surveillance
DME	Distance measurement system
EGNOS	European geostationnery overlay service (GNSS)
GPS	Global positionning system (USA)
ILS	Instrument landing system
NDB	Non directional beacon
MLS	Microwave landing system
VDL	VHF Data link (VDL, 2, 3, 4)
VOR	VHF omnidirectional ranging system
Regional groups	See next page
Technical groups	See next page
RNP	Required navigation performance
WAAS	Wide area augmentation system (GNSS)

REGIONAL GROUPS

EANPG	European air navigation planning group
ISPACG	Informal South Pacific coordination group
NATSPG	North atlantic special planning group
APANPIRG	Asia Pacific air navigation................
APIRG	Africa planning and implementing.....
Grepecas	Grupo.........Carribe y America del Sur
MIDANPIRG	Middle east air navigation..................

TECHNICAL GROUPS

AWOP	All weather operational panel
SICASP	Secondary radar improvement and collision avoidance panel
RGCSP	Review of the general concept of separation panel
OCP	Obstacle clearance panel
AMCP	Aeromobile communications panel
ADSP	Automatic dependant surveillance panel
ATNP	Aeronautical telecommunications network panel
GNSSP	Global navigation satellite system panel

SECTION 4

GLOBAL PLANNING

Global planning will be essential to the successful implementation of the new CNS/ATM systems. The global plan sets forth the details of this planning; the discussion in this section provides an overview of the key issues involved.

EVOLUTION AND TRANSITION

The need for an evolutionary transition is critical to planning for the new CNS/ATM systems:

An evolutionary transition is critical for planning the global implementation.

- The transition should be carefully planned to avoid degradation in system performance. The level of safety attainable today will need to be assured throughout the transition.
- Careful planning will also be necessary to ensure that aircraft of the future are not unnecessarily burdened by the need to carry a multiplicity of existing and new CNS equipment during a long transition cycle.
- As discussed in Section 3, there is a close relationship between the required CNS services and the desired level of ATM.
- For reasons of both economy and efficiency, it is necessary to ensure that differences in the pace of development around the world do not lead to incompatibility among elements of the over-all system. In particular, given the wide coverage of satellite CNS systems, world-wide co-ordination of these systems is necessary if they are to be optimized.

Key Transition Events

On a global scale, the transition to the ICAO CNS/ATM systems will be paced by a series of key events that must be completed for the implementation to proceed. Activities relating to those events are currently being pursued under the sponsorship of ICAO and/or its Contracting States. Global transition planning requires recognition and understanding of those events and the associated schedule of activities so that the individual planning undertaken by ICAO, States and international organizations can lead to the intended benefits. There are many such events, but for planning purposes it is useful to group them as follows:

- The availability of standards and procedures
- The completion of necessary trials and demonstrations
- The availability of adequate satellite capacity (when applicable)
- The equipage of suitable numbers of aircraft
- Operational use
- Training

Decisions on the elimination of current systems involve many factors.

It is recognized that there are major long-term consequences of adopting a CNS concept that will eventually permit the elimination of a variety of current CNS systems. Decisions on whether particular systems can be removed will depend on many factors. One essential factor is the demonstrated capability and implementation of the new systems. Moreover, a clear and compelling case for transition to the new CNS system will include consideration of the benefits perceived by the aviation community.

General Transition Issues

Human

- Procedures and training for use of parallel systems
- Human/machine interface issues for parallel systems
- Operator/user confidence in the new system
- Selection criteria for operators/users of the new system
- Procedures in case of new or old system failure
- Automation issues
- Operator knowledge of the system mix

Equipment/Facilities/Infrastructure

- Availability of equipment, facilities, and infrastructure for new and old systems
- Maintainability of new and old equipment, facilities, and infrastructure types
- Partial or non-standard equipage within a facility or aircraft
- Partial equipage across facilities or an aircraft fleet
- Integrity assurance and back-up for new and old systems
- Multiple equipment types or facilities for the same function
- Design of new systems to allow for further upgrade
- Replacement of aging components of the old system
- Upgrading of aircraft/facilities with limited remaining life
- Capacity and coverage issues
- Certification of equipment for the new system

Operational

- Use of different systems in different flight phases
- Different aircraft capabilities or user classes in the same airspace
- National or other boundaries with different infrastructures
- Non-equipped "intruders"
- Disruption of operations to change the system
- Supplementary versus sole-means use
- Aircraft/facilities out of service to re-equip
- Initial benefits of the new system during the transition

Management

- Standards and regulations
- Phased transition; intermediate steps
- Organizational restructuring during the transition
- Pre-operational trials
- Research and development and applications development
- Need and incentives to minimize the duration of the transition period
- Communication among States on implementation plans

Cost

- New system cost and investment in the old system; amortization
- Cost of maintaining parallel systems

Because of differences in the level of ATM in various parts of the world and the variety of other factors influencing the transition, exact time frames for the transition cannot be specified. However, considering the predicted occurrence of certain key events, the transition can be expected to occur during four time periods:

Rough time periods for the transition can be given.

- Previous term: TO -1992
- Near term: 1993-1995
- Mid-term: 1996-1999
- Long term: 2000-2010

Graphical depictions of the progress of the key events during these time periods for communications, navigation, and surveillance are shown in the system evolution charts on the succeeding pages.

Ideally, the transition to new CNS systems should be based on improvements in ATM, and should be accompanied by structural and procedural changes that will enhance ATM and provide benefits to users. The necessary structural changes involve airspace re-organization required to optimize the new systems. The necessary procedural changes include:

Structural and procedural changes will be required.

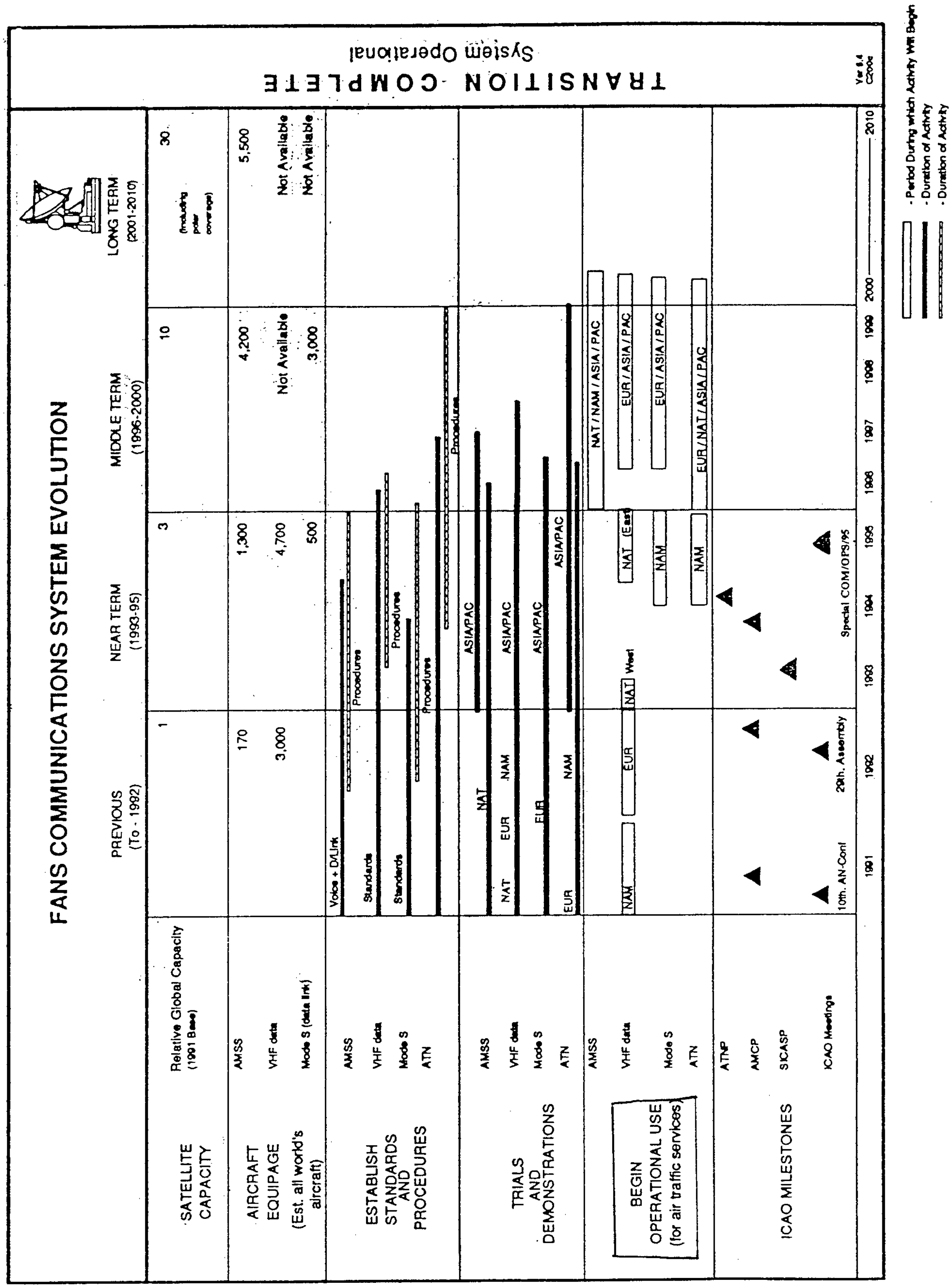
- Data link handling procedures
- Review of ATC procedures, including separation criteria
- Review of separation minima
- Message formats
- Approach procedures

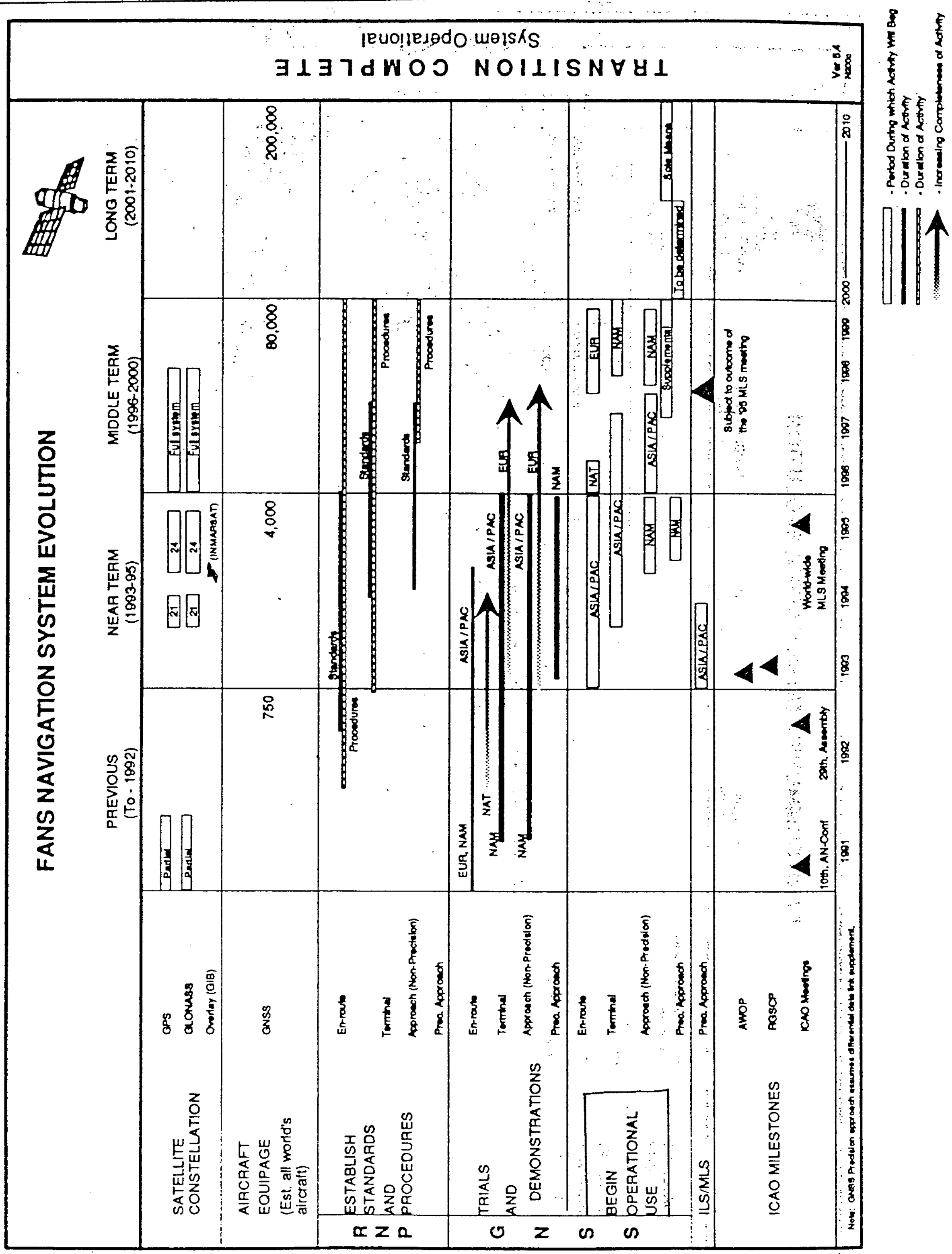
Planning and implementation of improved ATM capabilities should include consideration of human factors impacts and requirements. Essential human factors considerations for the transition include:

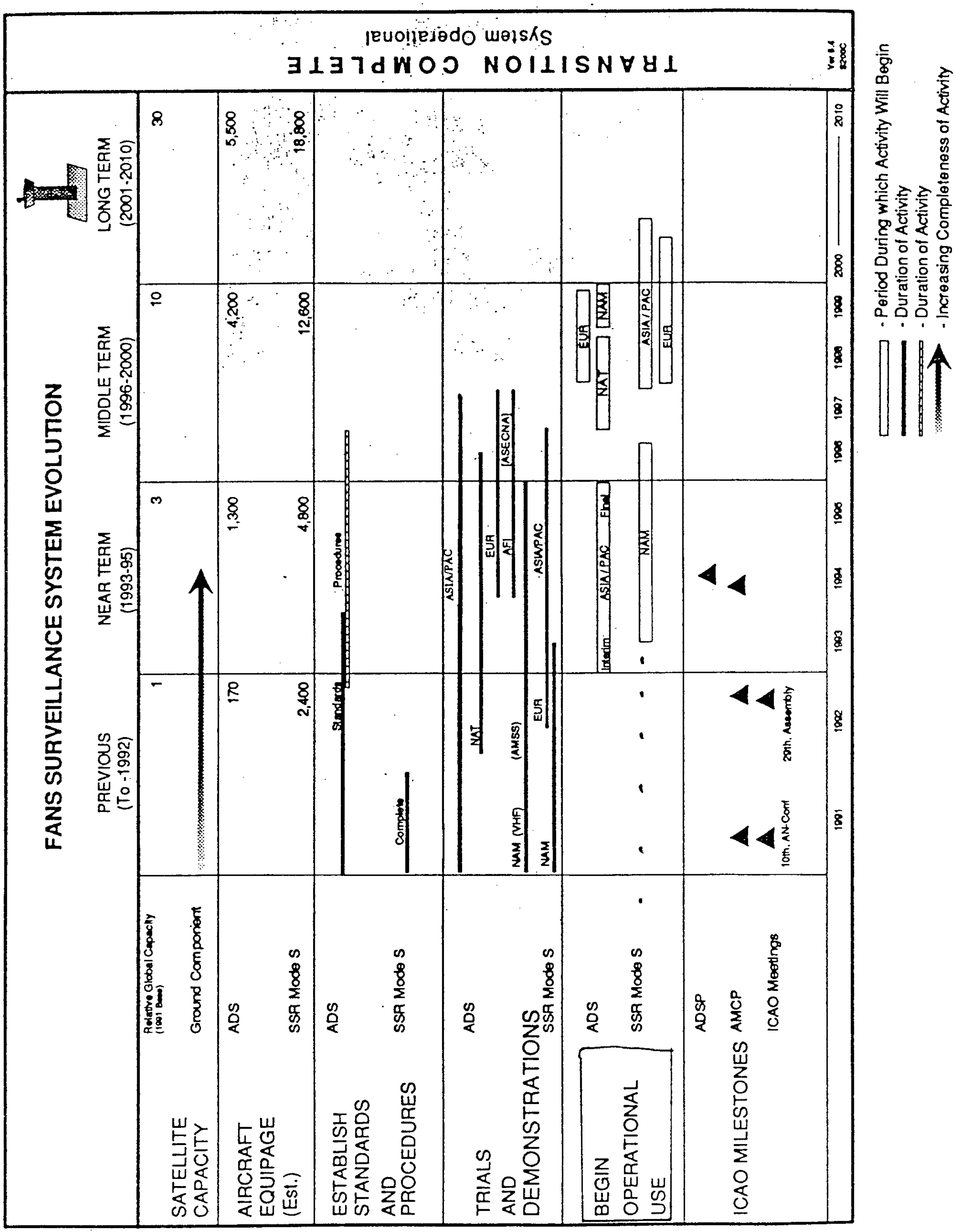
There are essential human factors considerations for the transition.

- Training (discussed below)
- Human/machine interface
- Definition of safety level with reference to system statistics as well as human capabilities and limitations
- The retention of situational awareness by ATS personnel and air crews

- Provision for user-preferred routings
- Effective packaging and managing of information relevant to users and ATS personnel
- Definition of responsibilities of pilots, air traffic controllers and system designers in an automated environment


FANS COMMUNICATIONS SYSTEM EVOLUTION
PREVIOUS (To - 1992)
NEAR TERM (1993-95)
MIDDLE TERM (1996-2000)
LONG TERM (2001-2010)
SATELLITE CAPACITY
Relative Global Capacity (1991 Base)
1
3
10
30 (including polar coverage)
AIRCRAFT EQUIPAGE (Est. all world's aircraft)
AMSS
VHF data
Mode S (data link)
170
3,000
1,300
4,700
500
4,200
Not Available
3,000
5,500
Not Available
Not Available
ESTABLISH STANDARDS AND PROCEDURES
AMSS
VHF data
Mode S
ATN
Voice + D/Link
Procedures
Standards
Procedures
Standards
Procedures
Procedures
TRIALS AND DEMONSTRATIONS
AMSS
VHF data
Mode S
ATN
NAT
ASIA/PAC
NAT EUR NAM
ASIA/PAC
EUR
ASIA/PAC
EUR NAM
ASIA/PAC
BEGIN OPERATIONAL USE (for air traffic services)
AMSS
VHF data
Mode S
ATN
NAT / NAM / ASIA / PAC
NAM
EUR
NAT West
NAT (East)
EUR / ASIA / PAC
NAM
EUR / ASIA / PAC
NAM
EUR / NAT / ASIA / PAC
ICAO MILESTONES
ATNP
AMCP
SICASP
ICAO Meetings
10th. AN-Conf
29th. Assembly
Special COM/OPS/95
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2010
TRANSITION COMPLETE
System Operational
Ver 8.4
C200c
- Period During which Activity Will Begin
- Duration of Activity
- Duration of Activity


FANS NAVIGATION SYSTEM EVOLUTION
PREVIOUS (To - 1992)
NEAR TERM (1993-95)
MIDDLE TERM (1996-2000)
LONG TERM (2001-2010)
TRANSITION COMPLETE
System Operational
SATELLITE CONSTELLATION
GPS
GLONASS
Overlay (GIB)
Partial
21
24
(INMARSAT)
Full system
AIRCRAFT EQUIPAGE (Est. all world's aircraft)
GNSS
750
4,000
80,000
200,000
RNP
ESTABLISH STANDARDS AND PROCEDURES
En-route
Terminal
Approach (Non-Precision)
Prec. Approach
Standards
Procedures
GNSS
TRIALS AND DEMONSTRATIONS
EUR, NAM
NAT
NAM
ASIA / PAC
EUR
BEGIN OPERATIONAL USE
NAT
To be determined
Sole Means
Supplemental
ILS/MLS
ICAO MILESTONES
AWOP
RGSCP
ICAO Meetings
10th. AN-Conf
29th. Assembly
World-wide MLS Meeting
Subject to outcome of the '95 MLS meeting
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2010
Ver 5.4
Note: GNSS Precision approach assumes differential data link supplement.
- Period During which Activity Will Begin
- Duration of Activity
- Duration of Activity
- Increasing Completeness of Activity


FANS SURVEILLANCE SYSTEM EVOLUTION
PREVIOUS (To -1992)
NEAR TERM (1993-95)
MIDDLE TERM (1996-2000)
LONG TERM (2001-2010)
TRANSITION COMPLETE
System Operational
SATELLITE CAPACITY
Relative Global Capacity (1991 Base)
Ground Component
1
3
10
30
AIRCRAFT EQUIPAGE (Est.)
ADS
SSR Mode S
170
1,300
4,200
5,500
2,400
4,800
12,600
18,800
ESTABLISH STANDARDS AND PROCEDURES
Standards
Procedures
Complete
TRIALS AND DEMONSTRATIONS
ASIA/PAC
NAT
EUR
AFI
(ASECNA)
NAM (VHF)
(AMSS)
ASIA/PAC
NAM
BEGIN OPERATIONAL USE
Interim
ASIA/PAC
Final
NAT
EUR
NAM
ASIA/PAC
ICAO MILESTONES
ADSP
AMCP
ICAO Meetings
10th. AN-Conf
29th. Assembly
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2010
- Period During which Activity Will Begin
- Duration of Activity
- Duration of Activity
- Increasing Completeness of Activity

SECTION 5

SYSTEM IMPLEMENTATION

The action programme for transition to and implementation of the new CNS/ATM systems includes guidelines and key activities for the States/regions, users, service providers, and ICAO.

The action programme outlined in this section is intended to provide users, service providers, and the States/regions with guidelines for transition to and implementation of the new CNS/ATM systems. The discussion below is at a high level of detail, in keeping with the spirit of the present document. Much greater detail on these issues is provided in the global plan.

The action programme provides transition and implementation guidelines.

TRANSITION GUIDELINES

Guidelines for transition to the future system encourage early equipage by users for the earliest possible accrual of the system benefits. Although a transition period of dual equipage, both airborne and ground, will be necessary to ensure the reliability and availability of the new system, the guidelines are aimed at minimizing this period to the extent practicable.

These guidelines emphasize early user equipage and minimizing of the dual equipage period.

*Guidelines for transition to the new communications system**

- States should begin to use data link systems as soon as possible after they become available.
- Transition to the aeronautical mobile-satellite service (AMSS) should initially be in oceanic airspace and in continental en-route airspace with low-density traffic.
- States/regions should co-ordinate to ensure that where ATC applications supported by AMSS are to be introduced, they should be introduced approximately simultaneously in adjacent flight information regions (FIRs) through which there are major traffic flows.
- During the transition period after AMSS is introduced, the current levels of integrity, reliability, and availability of existing HF communications systems must be maintained.
- Communications networks between ATC facilities within a State and ATC facilities in adjacent States should be established if they do not already exist.
- The aeronautical telecommunication network (ATN) should be implemented in phases.
- If new application message processors and data link systems are implemented, they should support code- and byte-independent data transmission and be fully compatible with the ATN.
- During the transition, States should co-operate on a bilateral and multilateral basis to ensure operation of the ATN meets the needs of international aviation and the States.
- States should establish procedures to ensure that both security and interoperability aspects of the ATN are not compromised.

* Global co-ordinated plan for transition to the ICAO CNS/ATM systems

*Guidelines for transition to the new navigation system**

- The global navigation satellite system (GNSS) should be permitted for supplemental en-route use first, and later for use as a sole-means system for en-route radio navigation.
- The ground infrastructure for current mandated navigation systems must remain available during the transition period.
- States/regions should consider segregating traffic according to navigation capability and granting preferred routes to aircraft with more accurate capability.
- States/regions should co-ordinate to ensure that separation standards and procedures for appropriately equipped aircraft are introduced approximately simultaneously in each FIR through which major traffic passes.

*Guidelines for transition to the new surveillance system**

- States should begin to develop operational procedures, in accordance with ICAO Standards and Recommended Practices (SARPs), procedures, and guidelines, for the implementation of automatic dependent surveillance (ADS) within airspace under their control.
- Transition to ADS should initially be in oceanic airspace and in continental en-route airspace with low-density traffic.
- States/regions should co-ordinate to ensure that where ADS is introduced, it is introduced approximately simultaneously in each FIR where major traffic flows occur.
- Where differing surveillance methods are employed in adjacent States or FIRs, commonality and comparability of systems are essential. Procedural means should be developed to make the service transparent to users.
- During the transition period after ADS is introduced, levels of integrity, reliability, and availability of existing position reporting systems must be maintained.
- States/regions should take actions within the ICAO framework to ensure that the implementation of procedural changes due to ADS and other systems will result in more efficient use of airspace.
- During the transition to ADS, suitability equipped aircraft should be given precedence over non-ADS-equipped aircraft for preferred routes and airspace.
- ADS should be introduced in phases.
- ADS equipment, standards, and procedures should be developed in such a way as to permit the use of ADS as a back-up for other surveillance methods.

* Global co-ordinated plan for transition to the ICAO CNS/ATM systems

The Way Forward, a European Perspective

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Slide 1

Good morning, ladies and gentlemen. I am honoured to present a paper to this distinguished audience. Here are some personal ideas about what may be coming next in European Air Traffic Management (ATM), dealing more specifically with the following items:

Slide 2

First, why is there is a need to act at all,
Second, try to explain existing plans in Europe to address challenges,
Third, show that we have at least some idea of how to address those challenges, by presenting some results, which will lead us to a possible path forward,
and finally to conclusions.

Slide 3

Air traffic in Europe has been growing heavily and steadily since 1985, at a compound rate of about 5% per year, reaching sometimes 10% a year. Traffic has doubled in about 12 years, which is an impressive growth, projected to carry on for the foreseeable future. This is the demand side.

Let's consider here four major indicators characterising ATM performance, the offer side.
Delays are one major ATM performance indicator. Imbalance between en route capacity and demand has resulted in large delays in the late 80's. It is remarkable that collective European action under EATCHIP was able to handle such traffic growth and to contain delays to tolerable levels. I shall present you the projection for delays if capacity is not increased further.
Delays are strongly related with capacity shortfall. Capacity shortfall can be analysed through modelling, taking traffic projections into account.
ATC costs, which are recovered through route charges in Europe, are another major performance indicator. I shall present the historic long term trend of ATC cost growth in Europe. There is a stronger and stronger pressure by airspace users to reduce ATM costs, whose magnitude is nowadays equivalent with that of fuel.

Collision avoidance between flights is the basic purpose of ATM. Safety is the fourth key ATM performance indicator. The natural law is that ATM-related incidents or accidents grow quadratically with traffic. Doubling traffic would imply four times more accidents, if countermeasures are not taken.

There are trade-offs between performance parameters. For example, it is possible to improve safety at the expense of cost. The converse is also possible, but should obviously handled with extreme care. The user requirement is to improve all performance parameters at the same time, while handling traffic growth. This is a considerable challenge.

Paper presented at an AGARD MSP Workshop on "Air Traffic Management", held in Budapest, Hungary, 27-29 May 1997, and published in R-825.

Slide 4

Now: What happens if capacity remains constant and traffic keeps growing?

Delays are directly linked with the imbalance between traffic demand and airspace/airport capacities. This slide shows how delays would grow if nothing was done, that is if no more capacity was created at airports and air traffic control centres. Delays, which are already considered to be barely bearable, would simply explode, even five years from now, that is tomorrow! Just remember that the growing delays at the end of the 1980's were at the origin of major political concern and resulted in the ECAC strategy for the 90's. It is clear we need an ECAC strategy for the 2000+, which is now being developed.

We have observed an empirical short term relationship between the difference traffic-capacity and delays with an elasticity of about 5. Typically, 1% more capacity reduces delays by about 5%, 1% more traffic at constant capacity increases delays by 5%. The explosive behaviour of delays matches well with this strong observed elasticity. There are two major components of growing delays: the blue line shows delays due to lack of ATM capacity, the green one delays due to lack of airport capacity. Whereas ATM capacity was dominant so far, airport capacity is projected to be dominant in the coming period, which brings us closer to the US case.

Slide 5

Coming now to cost trends. In Europe as you know, all revenues of air traffic control are recovered through route charges collected by The EUROCONTROL Central Route Charges Office, which amounts to about 5 billion dollars per year. This is of the same order of magnitude as fuel expenditure. Airlines are ready to invest a lot to save just 1% of fuel. ATM is far from being optimised to 1%. Imagine the pressure on ATM cost reduction, because the same savings can be achieved by reducing ATM costs by 1%.

You see here a long term cost trend analysis, which shows that the unit cost of ATM capacity tends to be linear in constant currency, globally and locally for a given country, and that there are little scale effects. For example, the Netherlands, which deliver less service units (kilometres flown weighted by the square root of mass) than France, have an equivalent unit rate. It's encouraging in a way because, so far, we have been able to provide more capacity at constant unit cost. The short term trend would be that costs grow faster than traffic because the only way to increase capacity has so far been to add more sectors, which has decreasing returns. But over the year, thanks to a number of intelligent initiatives, it was possible to beat that decreasing returns trend. Curbing the long term linear cost trend and decreasing unit rates will be a major challenge in itself.

Slide 6

Finally, capacity. The important remark here is that the situation in Europe is very contrasted. Many control centres have and will still have excess capacity in 2001, given detailed traffic projections for individual city pairs. In a few control centres, there will be a capacity shortfall between 25 and 50%, if no action is taken, which would generate the huge delays shown above. It is not adequate to devise plans for Europe whereby capacity would be increased everywhere by say 25 % until to 2001. It would not be cost-effective to add capacity in areas which are and will be over capacity, because over-capacity causes additional costs. Conversely, under-capacity causes delays and other penalties which exceed direct cost savings, which, again, is away from the optimum. We know from recent studies that the optimum is around a capacity/demand ratio of 1.

Slide 7

I'm coming now to the second part of this paper: the European response to these challenges.

Slide 8

Several major actions to improve ATM in Europe are co-ordinated through EUROCONTROL, a 26-state organisation.

The first three were launched in the late 80's and early 90's:
- implementation of the CFMU - the Central Flow Management Unit,
- the EATCHIP Program - European ATC Harmonisation and Integration Programme,
- definition of the future European ATM System (EATMS).

The ECAC Strategy for the 90's final target is 1998. It is remarkable that it was possible through combined European action to handle growing traffic - doubling in 12 years, with delays and costs being contained within acceptable limits. So, we can say the strategy for the 90's has been successful.

However, a number of non-renewable capacity resources have been exhausted: the size of sectors has often been reduced to a minimum , and so on. We want to handle growing demand whilst maintaining or improving ATM performance for all above-mentioned indicators: delays, costs, safety. This is very much what the ATM 2000+ strategy is about. The launching event happened in February 97 with the MATSE 5 Transport Ministers Meeting. MATSE 5 decided the institutional arrangements, which should take legal form with the signature of the EUROCONTROL Revised Convention. Performance review, performance driven R&D programmes, very much in line with the FAA approach presented by Clyde, should play a major role.

In fact, I shall try to show through this briefing the necessity of the different components of that strategy. In order to clarify the terminology, EATMS is at the same time the target, the ultimate goal towards which our programmes are aligned, and the way towards that target.

Slide 9

Official EATMS vision and objectives have been agreed through a series of user consultation. The vision is to allow all airspace users the maximum freedom of movement subject to the needs for safety, cost effectiveness, environmental aspects and national security requirements. The main objectives are : safety, efficiency , uniformity, environment, capacity, cost effectiveness and national security. Those objectives are stated at the moment in a qualitative terms. We are working to quantify objectives and to understand trade-offs between contradicting objectives such as cost reduction and safety improvement.

Slide 10

ATM is not living in isolation. Key external trends influencing EATMS have been identified.
The first one is a growing and unavoidable economic pressure to reduce ATM induced costs.
The second is that independent performance review will be put in place.
The third one is that the hub-and-spoke operations are projected to expand in Europe.
There will be increasing pressure on airports and runways. Airports must be addressed with at least the same priority as Air Traffic Control has been so far.
The question of human resource management is also a key item.
Increasing use of new generic technologies - for a long time ATC has been using specific technologies - is foreseen: operating systems, computers, telecom networks and so on.
And finally, air and ground will be much more inter-dependent.

Slide 11

So, why can't we just carry on the old way which was to further divide the airspace, to split sectors? First, airspace division is reaching diminishing returns and even physical limits: in some sectors in Europe, flying time is no more than five to eight minutes. The ATM unit cost is too high. As was said, ATM charges sometimes exceed fuel costs. Controller workload, tactical controller workload in particular, has been the limiting factor so far. Airport capacity limitations will hurt more and more. Therefore, new approaches have to be introduced to address challenges ahead of us.

Slide 12

Let's try now to understand the guiding lines of EATMS. In the procedural ATC era of the 50's, controllers knew precisely where aircraft was from time to time; in the present radar era, which has been lasting since the late 60's, controllers know where and who aircraft are, but very little assistance is given to know where aircraft will be, the essential item. Being a pilot, I know that pilots must fly ahead of their machine. That's exactly the same for controllers.
So, knowing not only where aircraft are, but also where they will be through intent broadcast could be the origin of a new generation of ATM, and of a paradigm shift leading some way towards the solution.
In EATMS, it is not foreseen that automation will replace human judgement and decision, both in the air and on the ground. The system design should be human-centred, taking advantage of both human intelligence and computer power.

Slide 13

Another feature of the EATMS concept is the airspace structure, which would include three sorts of airspace:
- managed airspace, which is similar to today's controlled airspace, with either direct routing, 2D or 3D routes (e.g. SID/STAR). Responsibility for separation could be temporarily and explicitly transferred on board as is the case today with visual crossing,
- free-flight airspace, where the responsibility for separation assurance will be on-board. Some sort of authority checking that the rules-of-the-air are respected could be required,
- finally, unmanaged airspace, which is very similar to today's uncontrolled airspace.

Slide 14

So, I presented the challenge and major lines of the EATMS concept. What makes us think there is a chance to meet the challenge, that we will be able to handle growing traffic demand, and to improve performance? Well, there are some clues from on-going research that this can be done.

Slide 15

The first major item where we see significant capacity gain for en-route is RVSM, Reduced Vertical Separation Minima, whereby vertical separation above FL290 will be reduced from 2000 to 1000 feet. A number of simulations were conducted, in particular at the EUROCONTROL Experimental Centre, showing potential capacity gains in the order of 30%. This is worth about five years of traffic growth, enough time to develop more elaborate solutions. Simulations showed that the « double alternate » scheme, whereby two successive flight levels are in the same direction, is the best option. There, I would like to praise our Hungarian colleagues, whose participation in those simulations was very precious. There is now a European plan to implement continental RVSM by 2001, the final go-ahead being due in June.

Slide 16

Trying to understand what is coming next in terms of integrated air ground systems, it is useful to start where we were yesterday.

Air ground interaction in the early days was based essentially on voice, a very thin link between air and ground.

Slide 17

The present air-ground interaction is still mostly dependant on voice communications and can be characterised as loose air-ground coupling. In fact, the essential difference with the early days is the introduction of identified surveillance thanks to SSR and flight plan. SSR is the foundation for the level of ATC automation we know today, which gives reliable information on where aircraft are to the controllers. However, the even more crucial information on where aircraft will be is still far from perfect. There is no system support to ensure that planning information available on board and on the ground is consistent. Consistency is only ensured through a rather weak chain of voice communication and two human operators, pilot and controller, backed by work-load intensive procedures. This defeats investment both sides (e.g., 1% fuel savings thanks to FMS flight profile optimisation can be negated by 10% penalty due to ATC in the TMA). This also gives rise to a number of potential errors, such as altitude errors, which account for two thirds of all incidents, according to NASA ASRS.
Proven safety is the main advantage of present ATC system. It has however a number of drawbacks: it is certainly workload intensive, capacity is limited, with a probable capacity shortfall shortly after 2000 under today's operating principles and finally it is rather expensive with the cost of air traffic control reaching the cost of fuel in some areas.

Slide 18

PHARE (The Programme for Harmonised Research in Air Traffic Management Research in EUROCONTROL) is probably one of the most extensive research programme addressing Air-Ground coupling at the moment. It is run by major research establishments in Europe, with both ATC and aeronautic expertise, together with their parent ATC authorities. PHARE is funded 50/50 by EUROCONTROL and participants.

The PHARE model essentially uses data-link for trajectory negotiations, whereby a contract is established between air and ground. PHARE is based on powerful planning tools on the ground and on an experimental 4D FMS on board, the EFMS. The EFMS is capable of assembling a 4D flight path which respects constraints uplinked from the ground. It is controlled through a touch-screen interface. Note that the airborne part was only developed to the extent necessary for the programme, and should in no way be considered as definitive.

There are a number of expected benefits associated with the PHARE scenario:
-first, controller workload reduction, which leads to better productivity, increased capacity and reduced delays, Remember that radar controller workload is the limiting ATC capacity factor in Europe. If sector capacity was doubled, double traffic could be handled with present staffing, a yearly saving in the order of 1500 MECU by 2005.
-in addition, PHARE planning tools can support direct routing en route, which could yield yearly savings in the order of 400 MECU in Europe by 2005,
-finally, enhanced safety through consistency checking of air and ground planning information and medium term conflict detection and resolution.

Slide 19

The PHARE scenario relies on a number of advanced controller assistance tools. There are nine of those: the Trajectory Predictor, the Conflict Probe, the Flight Path Monitor, the Negotiation Manager, the Problem Solver, the Arrival Manager, the Departure Manager, the Tactical Load Smoother and the Co-operative Tools.

One of the new features of PHARE is the Problem Solver, which enables the controller to look into the future and design a plan which resolves conflicts for a given aircraft against all others over a given time horizon.

Slide 20

Before explaining the Principles of the Problem Solver, I would like you to understand that a time-dependant problem in our conventional 3D space is a static problem in a 4D space, including time as the fourth dimension. In this 4D space, each trajectory is a static curve, to which a protection volume can be associated. Flight planning can be considered as a problem of optimisation under constraints in a 4D space. Constraints outside the aircraft itself are essentially: terrain, traffic, flow, airspace and meteo. 4D protection volumes can be associated with all those constraints, which the subject aircraft 4D flight path should not intersect.
4D geometry is not readily understandable by humans. However, it is possible to compute 2D projections in this 4D plane. These 2D projections show intuitive maps of constraints in each of the three useful degrees of freedom of an aircraft, i.e. horizontal, longitudinal and vertical. Computing these 2D projections involves exact geometric transforms, which are easy for computers, however complex, and can be proven.

Back to the PHARE Problem Solver, which combines the power of computers for algorithms with the power of the human brain and vision for finding its way on a map, in a truly Human-centred approach. The Problem Solver shows what not to do, rather than telling what to do, like AERA for example. The horizontal display shows a map of traffic constraints for horizontal manoeuvres. An intuitive description of the horizontal 2D projection shows the contour of separation infringement segments from a given turning point.

Slide 21

With the Problem Solver, testing a horizontal resolution manoeuvre simply entails dragging the original flight path (the thin blue line), until it is clear from conflict zone. Note that the conflict zone has a dark core corresponding to the separation standard, and a lighter zone, which corresponds to prediction uncertainties. There, the controller can either decide to plan the shortest route and wait whether the conflict will eventually materialise, or plan a conservative route around the uncertainty zone and forget about the conflict. This is a very intuitive interaction which is readily learnt by controllers. Note that the controller can instantaneously decide whether the solution he/she has designed solves the conflict, and find the best solution, thereby remaining fully in control.

Slide 22

Similarly, constraints to speed and vertical changes are shown on two additional maps. The vertical axis of the speed display shows early/late arrival. An horizontal segment represents nominal speed, an upwards segment shows increasing speed, with faint triangles showing flyability limits. Note that the speed display enables the controller to decide instantaneously whether there is a speed change solution, and which is the best one, a novel feature. In the altitude change display, flight level is shown against time in the vertical display, together with traffic constraints zones. Interpretation is straightforward, with zones showing real and potential conflicts.

Note that any combination of heading, speed and altitude change for a given aircraft can be designed and checked very quickly with this system.

Slide 23

So, PHARE achieved already very significant steps towards a better air-ground integration. However, using lessons learnt, one could consider whether there are no alternative models, for example trying to loosen the air-ground coupling as compared to the PHARE scenario.
PHARE tools need good trajectory prediction. Such prediction is easy with 4D aircraft, because, by definition, they arrive at the said time and place. In this diagram, trajectory prediction would incorporate accurate MET and very accurate flight planning information which is available in AOC. The PHARE MET project indicates that it is probably possible to reduce the wind speed error from 15 knots to 5 knots rms. by incorporating aircraft reports in a background field, which is probably good enough to support the advanced tools. This is only a first step towards integrated air-ground systems.

Slide 24

Consider for one moment that the advanced planning information and tools available to the planning controller in PHARE are also available on board the aircraft. Suppose also that all constraints, i.e. traffic, terrain, airspace, MET and flow are incorporated on those 2D projections. That would give a powerful basis for dialogue between the controller and the pilot to establish an agreed path.
This slide shows constraints for horizontal planning: traffic, restricted airspace and Meteo in this case.

Slide 25

Such principles are being implemented in the experimental FREER project at the EUROCONTROL Experimental Centre. Under FREER 1, Problem Solver like displays are presented to professional pilots, in order to find whether such tools and associated procedures could usefully support Airborne Separation Assurance. This slide shows an early implementation o such a display. The more elaborated FREER 2 would support co-operative air-ground Separation Assurance, using similar information in the air and on the ground.

Slide 26

With consistent information across ATC centres and aircraft, and associated management tools, conflict resolution could be ground based, with controllers using advanced tools to plan conflict-free trajectories and identify constraints to be satisfied by the aircraft. Conflict resolution could be shared, with trajectories being negotiated between air and ground on the basis of a common information. Conflict resolution could possibly be handled on board the aircraft as well. Note that this would require the definition of extended rules of the air, which would define which aircraft is in charge of solving which conflict.

What would be necessary to that effect? I suggest that a consistent information base on all constraints, available to all interested parties, with access control for confidentiality and security reasons, together with associated management tools, would provide a good foundation.

Note the essential components of this model:
- aircraft with today's system (not necessarily 4D FMS), air-ground and air-air data-link capability for communicating position and intentions, using ATN and ADS-B for example,
-AOC, which may become a major player as we saw in the last slide,

-Airports, which could provide information such as runway capacity, and receive information such as expected landing times.
-Finally ATM as defined in EATMS, i.e. a seamless network of ATC centres and ATFM.

What could be expected from such a model?
-It could support the full spectrum of operational concepts, from 4D tubes to autonomous aircraft, depending on time and airspace, with a uniform underlying paradigm,
-It would enable trajectory negotiations and advanced planning, thereby drawing full benefit of air and ground automation. This does not contradict the principle of « Free Flight », because aircraft may modify intentions at any moment, provided they are communicated and satisfy constraints. It is rather a foundation for « Free flight », or rather « Efficient Flight ».
-And finally, it would provide safety back up loops, checking consistency of information between different players and identifying future conflicts.

Slide 27

I think we start to have a clearer view of a possible path forward, which could be capable of addressing the challenges mentioned above.

Slide 28

In addition to on-going initiatives on Central Flow Management (CFMU) and improvement of the present system, a first quantum jump in performance could come from RVSM, may be followed by direct routing in upper airspace. Tools like the Problem Solver, or its implementation called HIPS, would significantly help controllers in planning traffic outside classical route networks. The next step may be what is called here Co-operative ATM, with ATC, AOC, and aircraft being involved in the decision making process, based upon homogeneous information available to all concerned parties. A continuum of Separation Assurance principles, from ground-based ATC to airborne separation, with any form of negotiation in-between, could be based upon a uniform paradigm: flight planning taking into account all constraints (traffic, terrain, Meteo, ...) known to all concerned and possibly represented by no-go zones. Finally, we may one day reach the nirvana o free-flight.

Slides 29, 30

The following two slides give the axes for change as presently identified in the EATMS context.

Slide 31

As a conclusion, I would say that tough challenges lie ahead of us. In view of past effort known results, we can have good confidence that ATM challenges can be met. However, it was shown that airport challenges are of the same magnitude. The ATM 2000+ strategy being developed will most certainly be performance oriented, with priority being given to actions with best influence on performance. The very timely « gate-to-gate » approach will enable Europe to address airport challenges. Co-operative ATM may be a practical way to deliver a quantum jump in ATM performance, with enough capacity and efficiency to handle growing traffic at acceptable cost. This will not happen over night, and will require everybody's effort to achieve progressive implementation.
Thank you.

EUROCONTROL

Plans and prospective a European view

29 May 1997

Xavier Fron
EUROCONTROL Experimental Center

EUROCONTROL

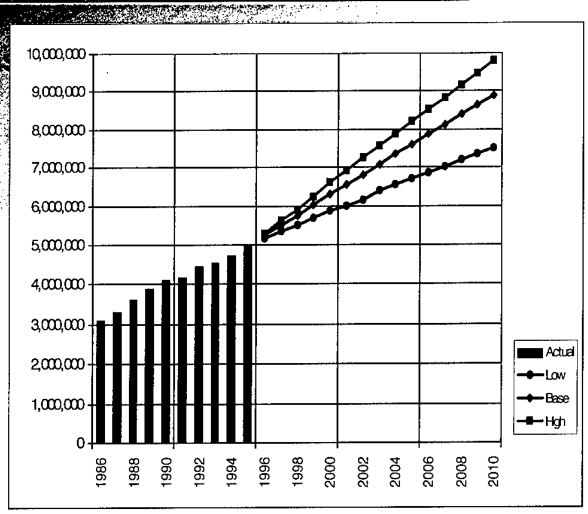
Presentation Content

1. European Challenge
2. EATMS Target
3. Some results
4. Path Forward
5. Conclusion

EUROCONTR(

European challenge

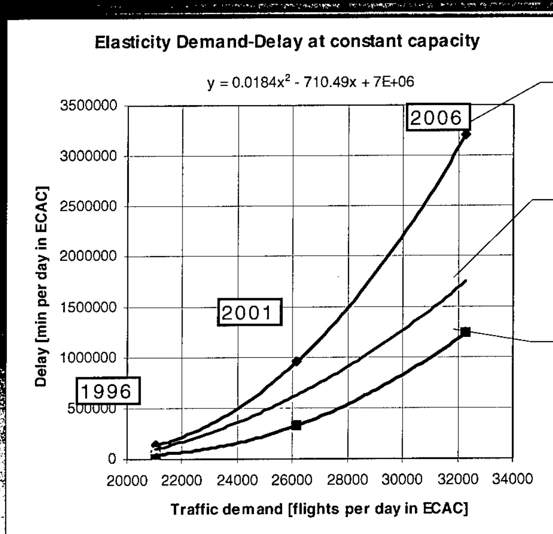
- Forecast traffic increa
- Delay trends
- Cost trends
- Capacity shortfall
- Future safety levels



3 **European challenge (1/4)** Plans and prospective: a European View

EUROCONTF

Delay forecast (do nothing)



Total delay due to ACC AND airport capacity shortfalls

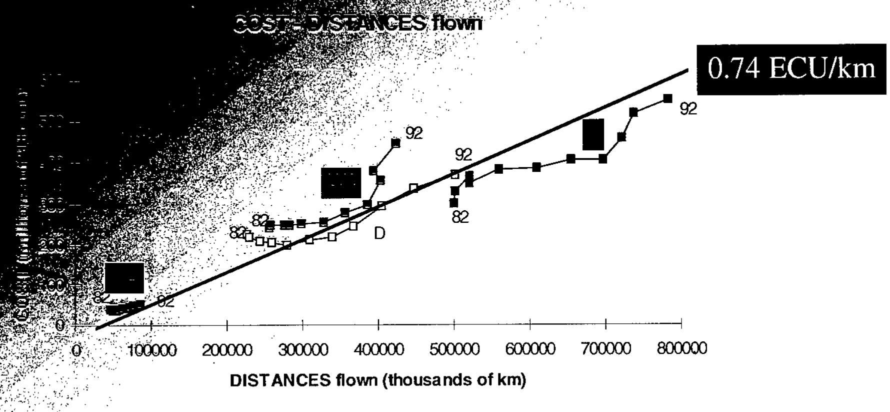
Delay due to **airport** capacity shortfalls (with ACC capacity constraint)

Delay due to **ACC** capacity shortfalls (with airport capacity constraint)

4 **European challenge (2/4)** Plans and prospective: a European View

EUROCONTR

Cost trend

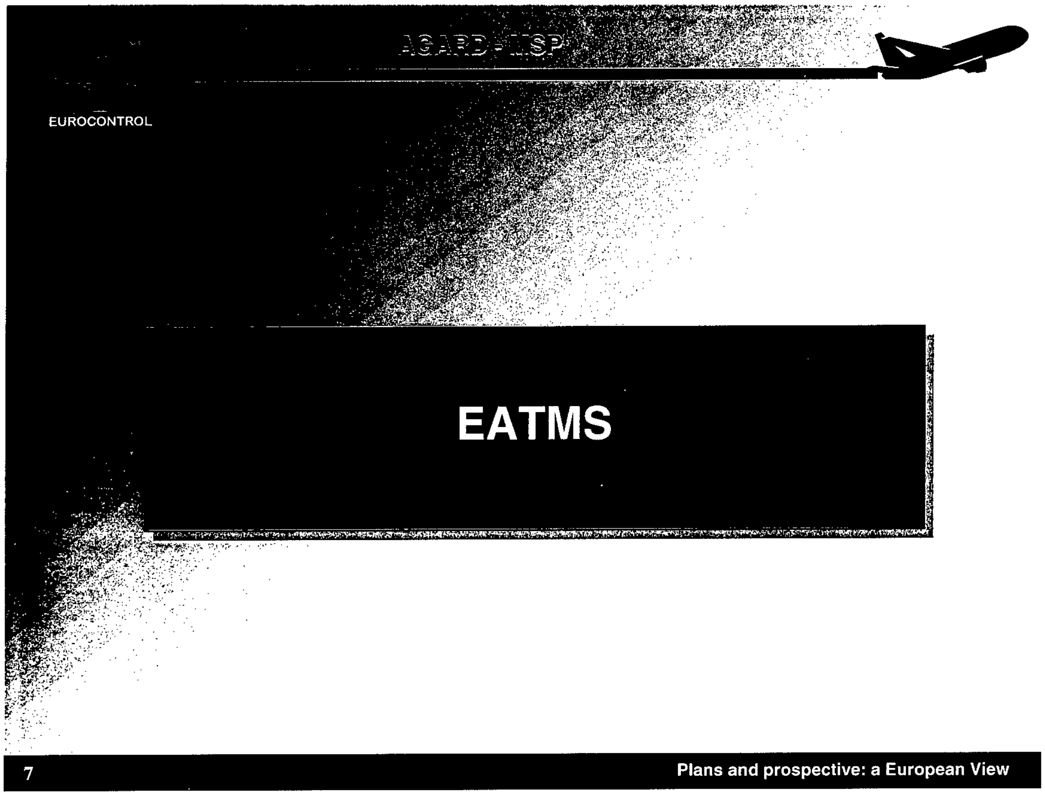


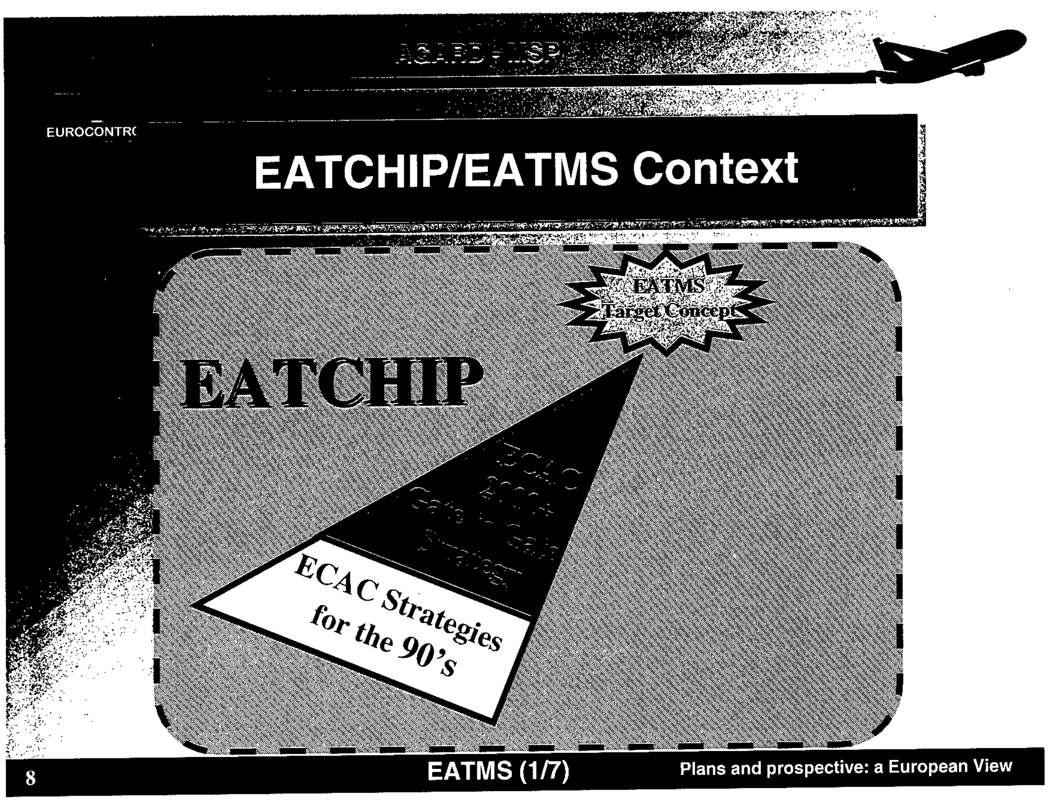
Linear trend (long term)

EUROCONTR

Capacity shortfall

Contrasted picture


EUROCONTROL
EATMS
7
Plans and prospective: a European View


EUROCONTR
EATCHIP/EATMS Context
EATMS
Target Concept
EATCHIP
ECAC Strategies
for the 90's
8
EATMS (1/7)
Plans and prospective: a European View

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EUROCONTRO

The EATMS Goals

The Vision: [illegible]

Main Objectives: [illegible]

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External trends in ATM Environment

Top 7 trends from a recent workshop

- Economical competition and pressure on costs
- Independent performance review
- Continuation of Hub and Spoke operations
- Increasing pressure on Airports/Runways
- Improved Human Resource management methods
- Use of generic technologies
- Air & ground system interdependency

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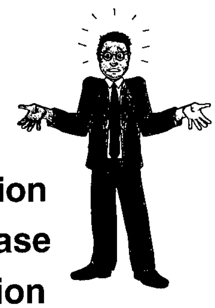
Why New Concepts?



ATM:

- Low return of further airspace division
- High unit cost => Productivity increase
- Tactical Controller workload limitation
- Airport capacity
- Flight efficiency

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EUROCONTROL

From Demand to Capacity Management

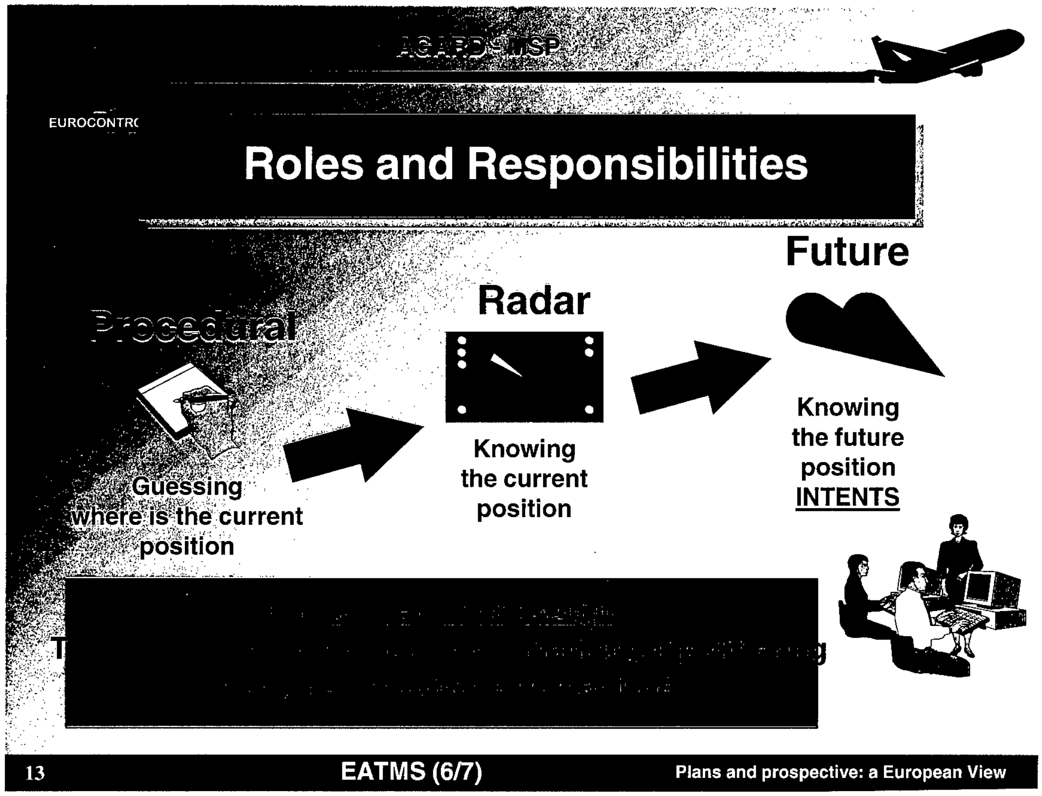
Capacity Management based on:

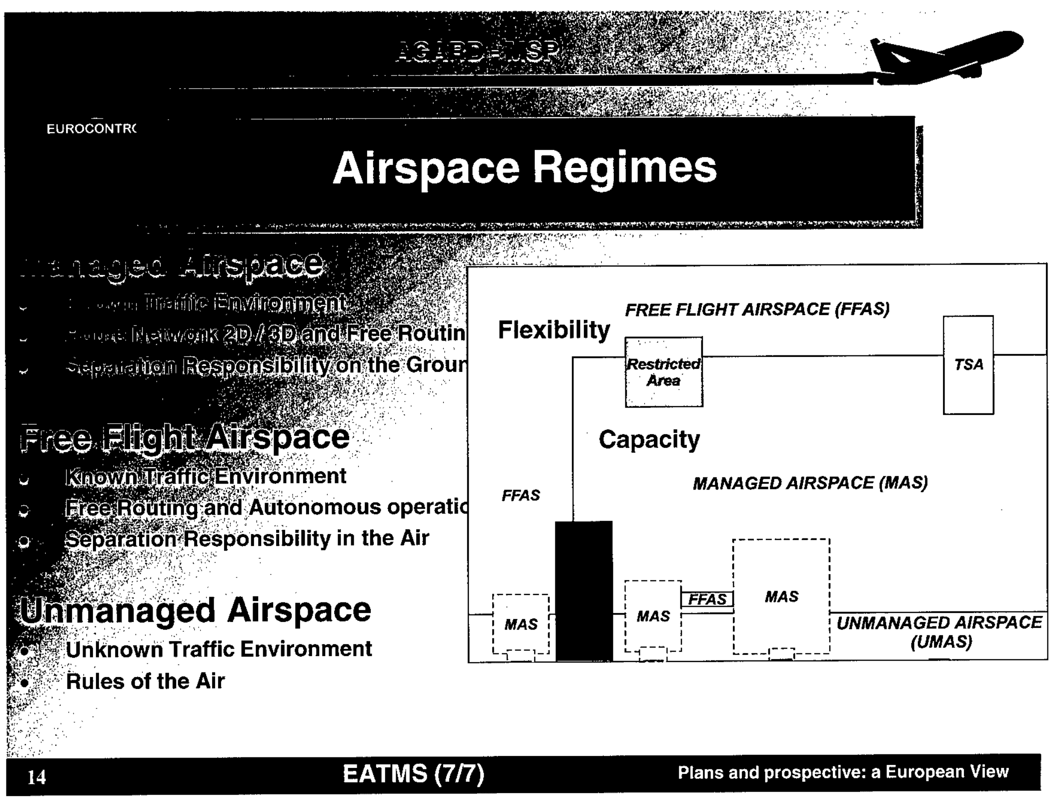
- Service quality agreements
- Collaborative & layered sets of planning functions

Safety
Punctuality
Efficiency

STRATEGIC PLAN — DAILY PLAN

Strategic Flow Scheduling	Pre-Tactical Flow Regulation	Tactical Flow Planning


AGARD MSP
Roles and Responsibilities
Procedural
Guessing
where is the current
position
Radar
Knowing
the current
position
Future
Knowing
the future
position
INTENTS
13
EATMS (6/7)
Plans and prospective: a European View


AGARD MSP
Airspace Regimes
Managed Airspace
Traffic Environment
Network 2D/3D and Free Routin
Separation Responsibility on the Grour
Free Flight Airspace
Known Traffic Environment
Free Routing and Autonomous operatio
Separation Responsibility in the Air
Unmanaged Airspace
Unknown Traffic Environment
Rules of the Air
Flexibility
FREE FLIGHT AIRSPACE (FFAS)
Restricted Area
TSA
Capacity
MANAGED AIRSPACE (MAS)
FFAS
MAS
MAS
FFAS
MAS
UNMANAGED AIRSPACE (UMAS)
14
EATMS (7/7)
Plans and prospective: a European View

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Some results

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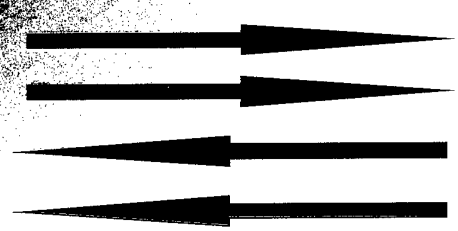
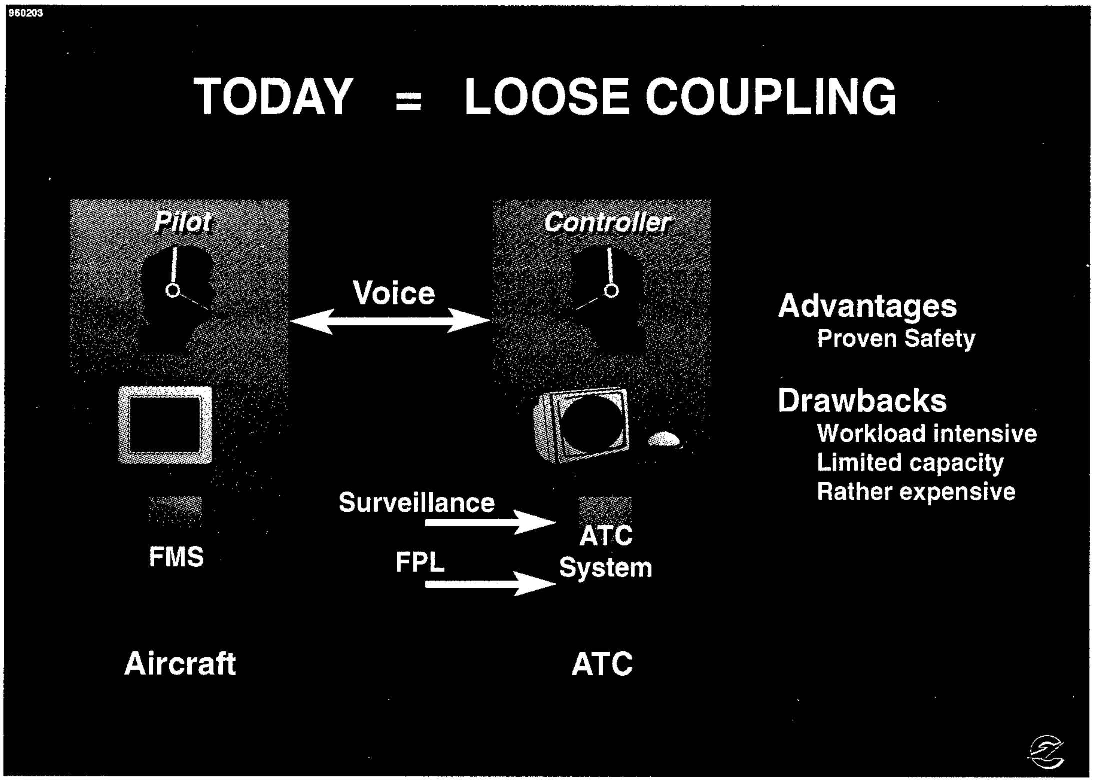
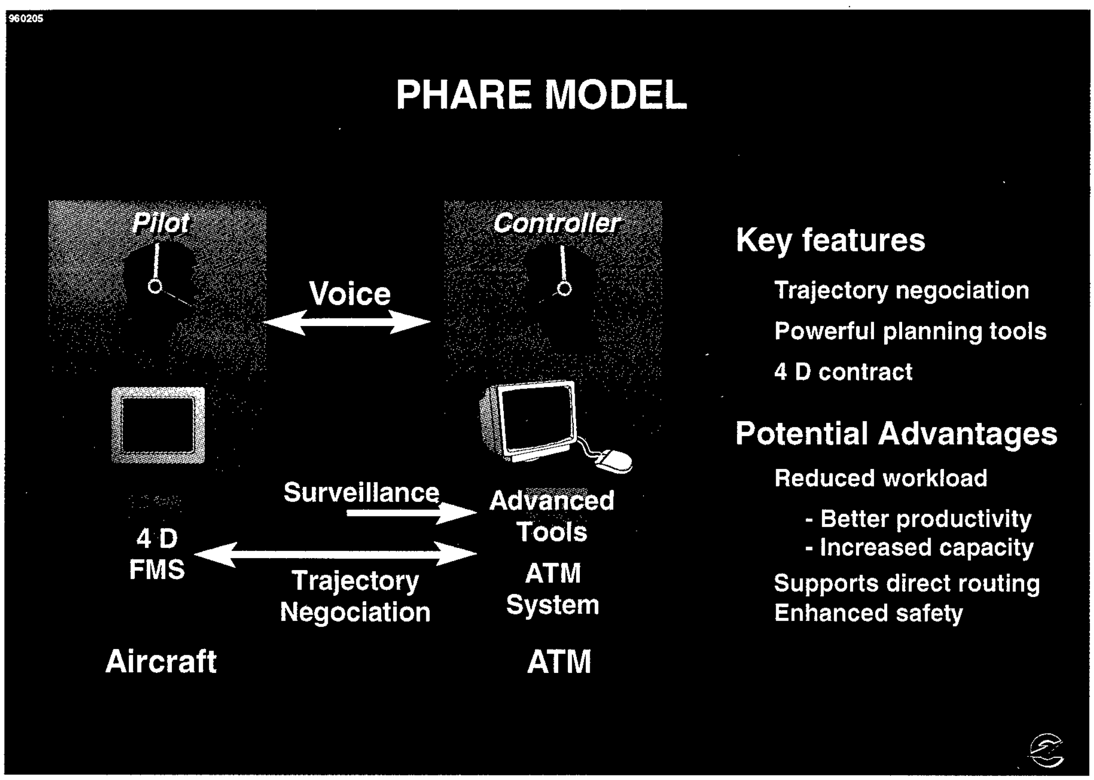
Continental RVSM

- Target implementation date: 2001
- High capacity gains demonstrated in simulation
- "Double alternate" is best option
- Buys some time for more elaborate solutions




960203
TODAY = LOOSE COUPLING
Pilot
Controller
Voice
Advantages
Proven Safety
Drawbacks
Workload intensive
Limited capacity
Rather expensive
Surveillance
FPL
FMS
ATC
System
Aircraft
ATC


960205
PHARE MODEL
Pilot
Controller
Voice
Key features
Trajectory negociation
Powerful planning tools
4 D contract
Potential Advantages
Reduced workload
- Better productivity
- Increased capacity
Supports direct routing
Enhanced safety
Surveillance
Advanced
Tools
ATM
System
4 D
FMS
Trajectory
Negociation
Aircraft
ATM

960227

PHARE ADVANCED TOOLS (PATs)

Ground System Functions

Trajectory Predictor (TP)
Prediction of the onward path of the aircraft in 4 dimensions

Conflicts Probe (CP)
Prediction of conflicts based on the predicted trajectories of the TP

Flight Path Monitor (FPM)
Automatic detection of deviations from planned flight trajectories

Negociation Manager (NM)
Processing of air-ground and ground-ground communication of trajectory requests and assignments (different scenarios for achieving a "contract")

Problem Solver (PS)
Proposals for the resolution of the conflicts of the CP or other problems

Arrival Manager (AM)
Provision of optimum scheduling and sequencing advisories to ATC controller for inbound traffic in the TMA

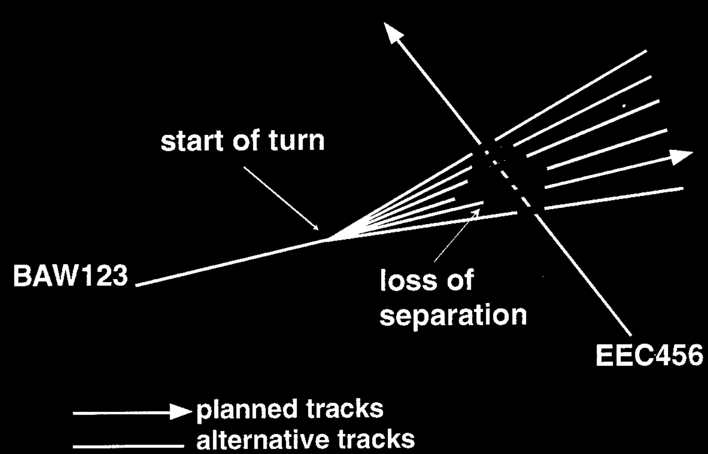
Departure Manager (DM)
Provision of optimum departure advisories to ensure efficient flow of outbound traffic into the en-route sector

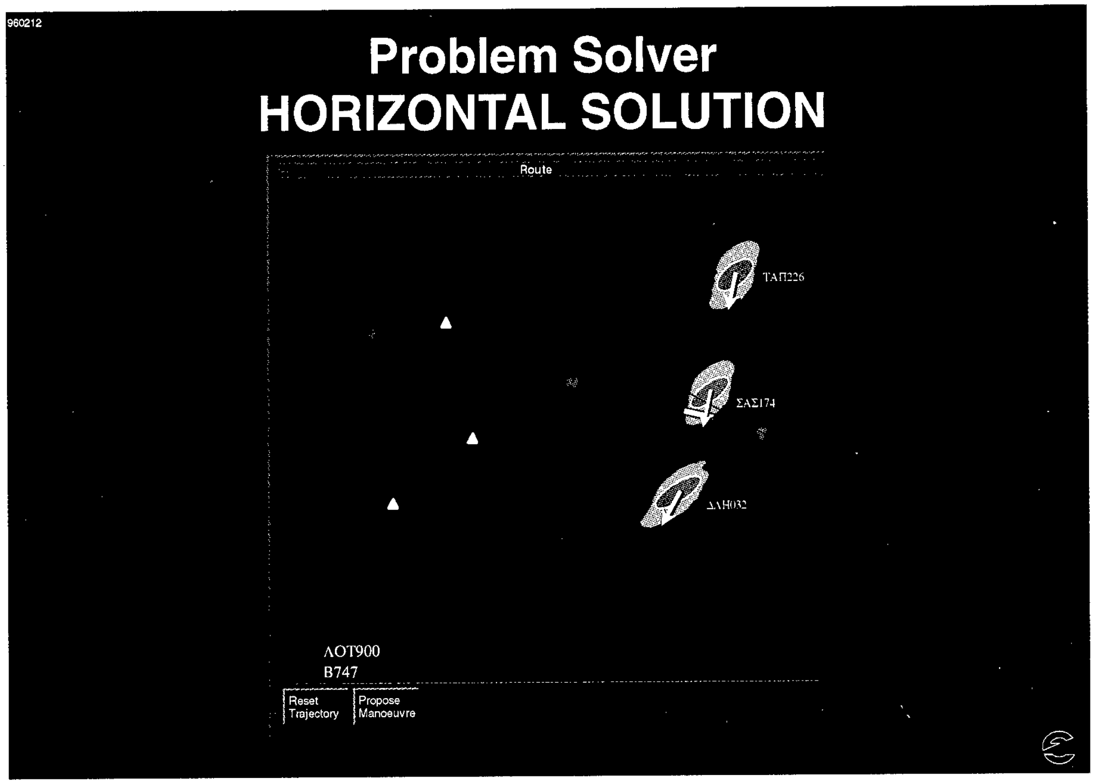
Tactical Load Smoother (TLS)
Multi-sector planning tool related to advanced scenarios of PHARE Demonstration 3

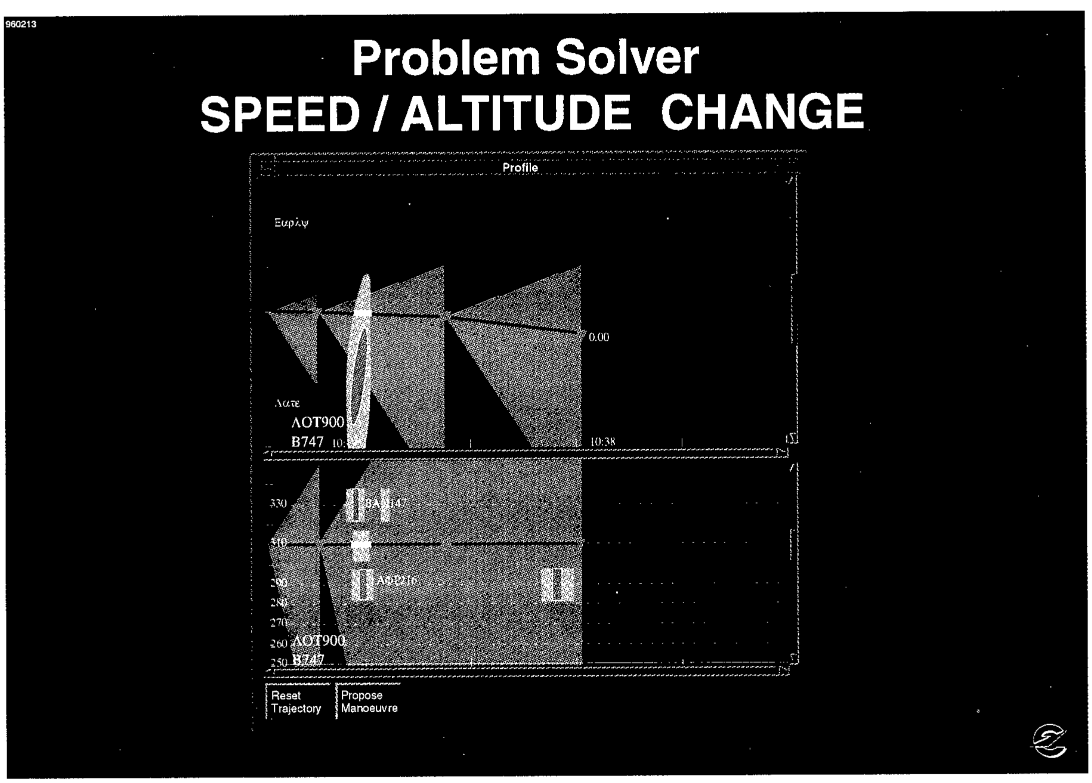
Cooperative Tools (CT)
"Electronic assistance" tool encompassing the other 8 tools above in the PHARE Demonstration 3

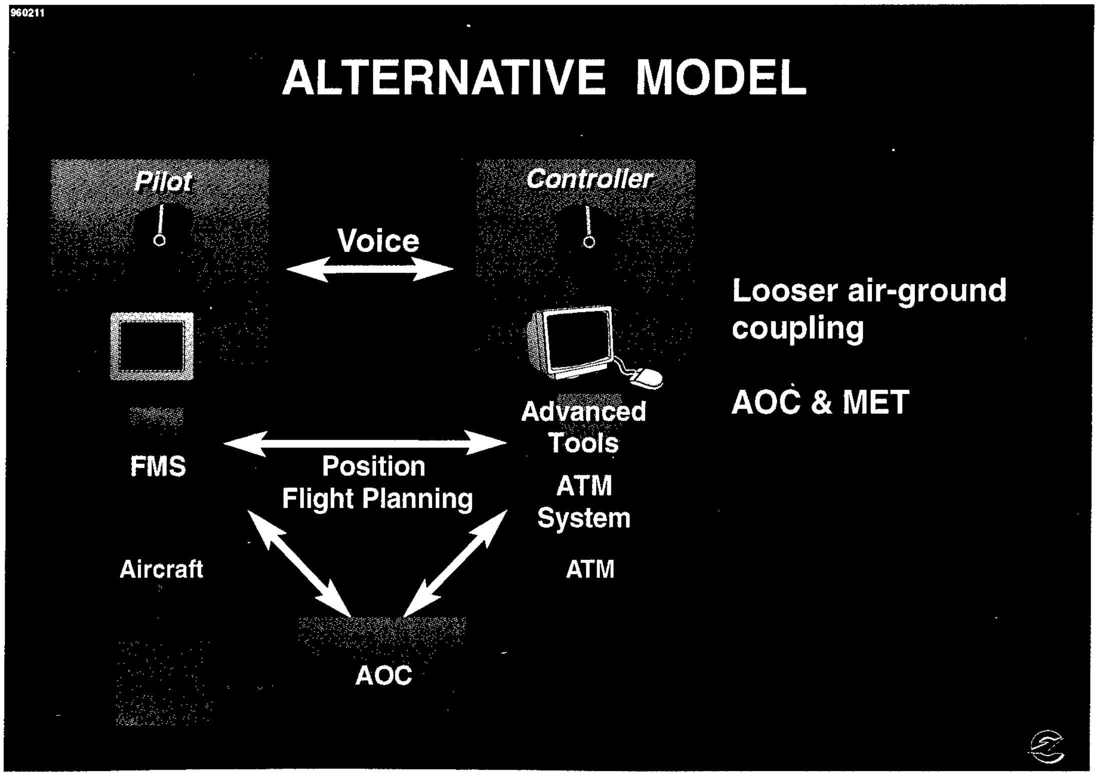
960214

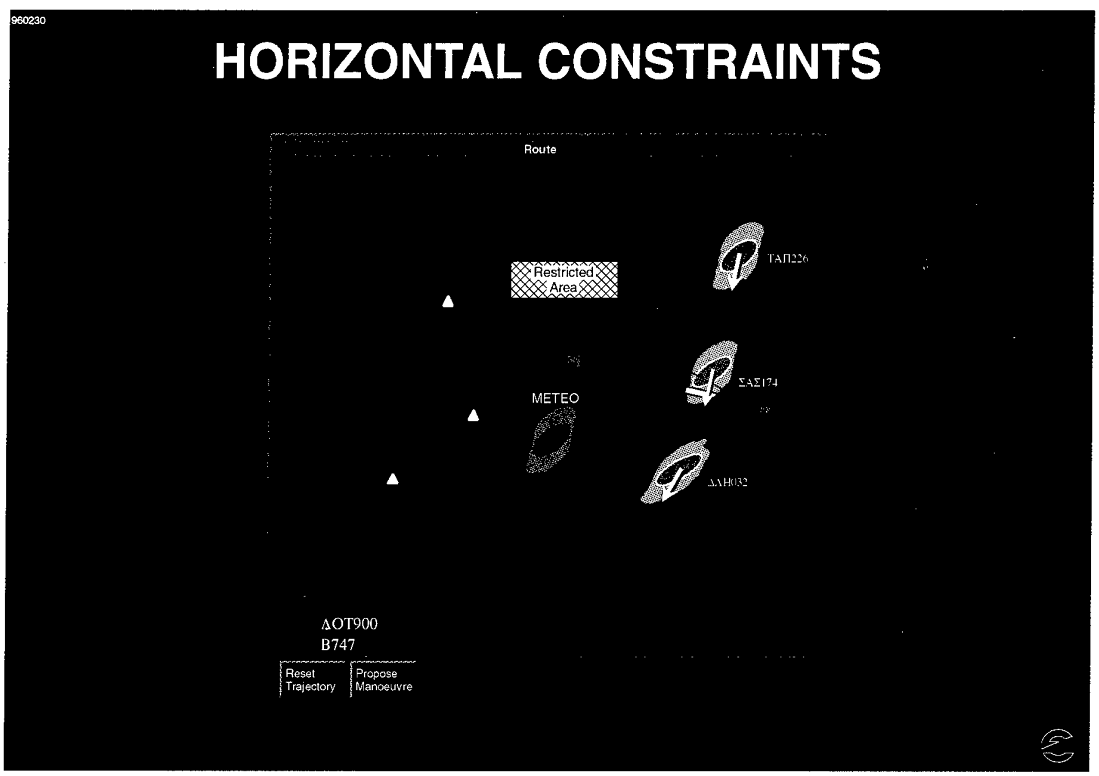
Problem Solver HORIZONTAL DISPLAY

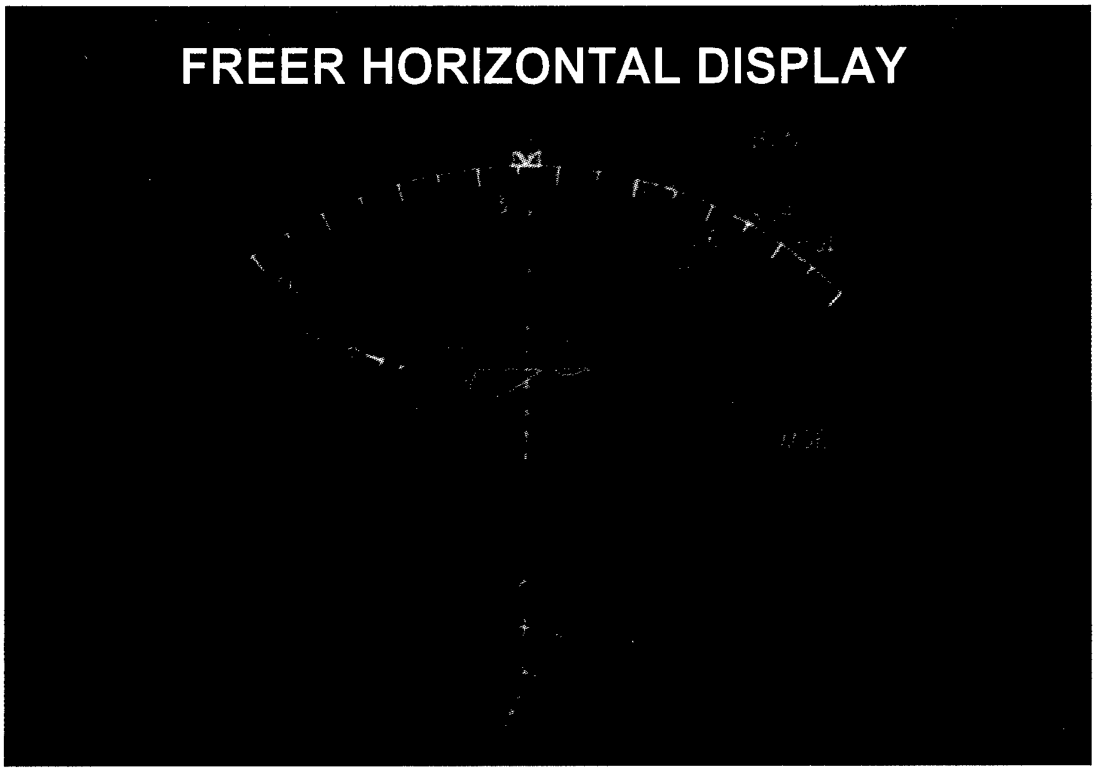


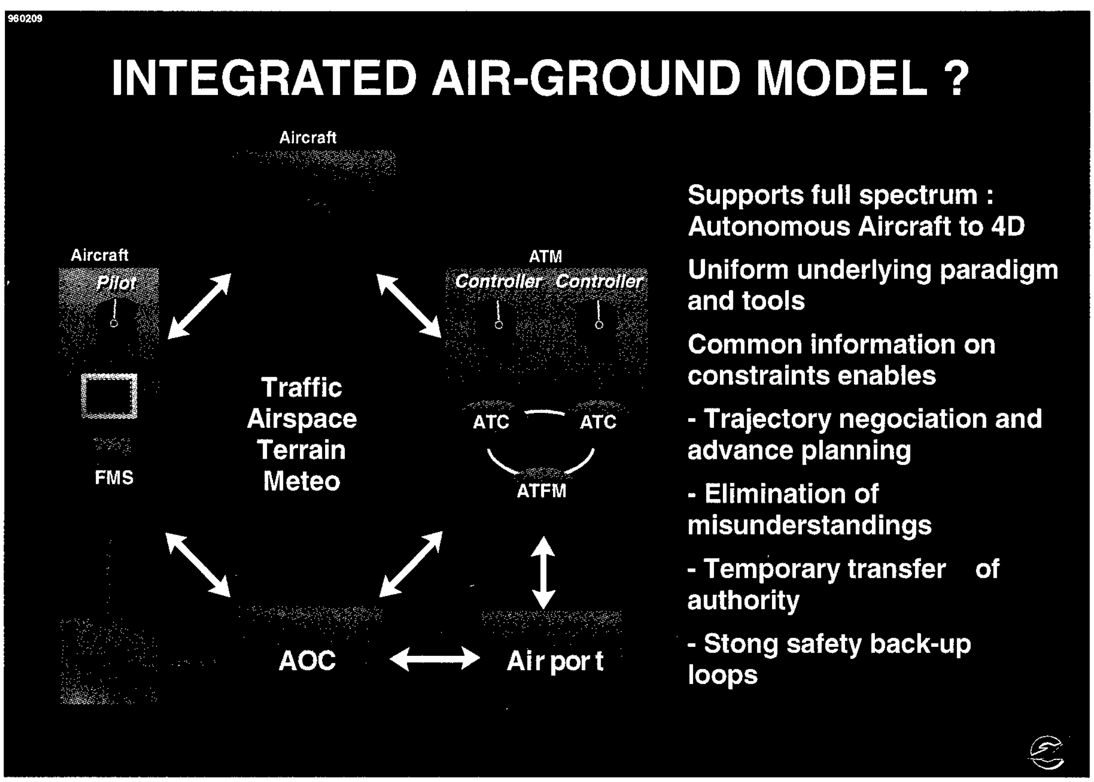

960212
Problem Solver
HORIZONTAL SOLUTION
Route
ΑΟΤ900
B747
Reset Trajectory
Propose Manoeuvre


960213
Problem Solver
SPEED / ALTITUDE CHANGE
Profile
0.00
ΑΟΤ900
B747
10:38
330
310
270
260
250
ΑΟΤ900
B747
Reset Trajectory
Propose Manoeuvre


960211
ALTERNATIVE MODEL
Pilot
Controller
Voice
Looser air-ground coupling
AOC & MET
Advanced Tools
FMS
Position
Flight Planning
ATM System
Aircraft
ATM
AOC


960230
HORIZONTAL CONSTRAINTS
Route
Restricted Area
METEO
ΑΟΤ900
B747
Reset Trajectory
Propose Manoeuvre


FREER HORIZONTAL DISPLAY


960209
INTEGRATED AIR-GROUND MODEL ?
Aircraft
Aircraft
Pilot
ATM
Controller Controller
Traffic
Airspace
Terrain
Meteo
FMS
ATC
ATC
ATFM
AOC
Air port
Supports full spectrum :
Autonomous Aircraft to 4D
Uniform underlying paradigm and tools
Common information on constraints enables
- Trajectory negociation and advance planning
- Elimination of misunderstandings
- Temporary transfer of authority
- Stong safety back-up loops

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The Path Forward

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Axes for Change

- 2000 -----> 2005
  - Improvements to structure and use of airspace and airport resources
  - Introduction of new, open data processing systems
  - Computerised support for tactical ATC functions
- 2002 -----> 2006
  - Introduction of free routings starting in upper airspace

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Axes for Change

2005 -----> 2012

Enhanced planning functions

Increased user involvement in real-time decisions

Runways/CNS-ATM infrastructure optimisation

Low visibility enhanced airport capacity

Air-ground integration

Gate-to-gate integration

2010 -----> 2015

Redistribution of responsibilities

Maximise freedom of movement

23 The Path Forward (2/2) Plans and prospective: a European View

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Conclusions

EATMS Strategy

Some possible features

- Performance oriented
- EATMS target
  - Gate-to-Gate
  - Co-operative ATM
- Progressive implementation

24 Plans and prospective: a European View

ANNEX
CONFERENCE SESSION DISCUSSIONS
Carlos Garcia-Avello
Editor

TRANSCRIPTION QUESTIONS - REPLIES

SESSION 1

NAME M. PELEGRIN

COMPANY ANAE

COMMENT Comment about a remark made by Gen. ALEXIS

TEXT There is a strong difference between landing and take-off. In the first case the plane should pass from a barometric altitude (or height) reference to a ground referenced trajectory. This is why the safest and most precise landings are performed with the ILS. On the contrary at take-off the plane quit the ground and get a barometric altitude (or height according to the baro-reference used on the altimeter).

ANSWER For evident safety reasons the plane must accelerate as rapidly as possible and once it reached the "rotation speed Vr" it must take off. The point on the runway at which the plane takes off varies in a large domain while the point at which the plane touchdown is located in a very short domain at about 300 m from the runway threshold.

After take off one can imagine that the plane will fly horizontally at a height of some tens of meters and wait for the glide slope normally used for landings in the opposite QFU.

NAME A. BENOIT

COMPANY EUROCONTROL

QUESTION TO U. VÖELCKERS

TEXT

1 20 Years ago, we made predictions of the future position of the aircraft; these were accurate for short periods of time only, the volume of uncertainty becoming quickly prohibitive. Subsequently, we designed a ground-based control system which made it possible to maintain the time of arrival over a fixed geographical point within a few seconds after a one-hour flight, for instance.

You are in fact defining the initial conditions of a flight, if the flight is considered being initiated at brake release.

In view of your experience, the number of uncertainty sources clearly mentioned in your diagrams, what can be expected as brake release time accuracy versus prediction horizon ?

2. In the planning and monitoring frame, you refer to predictions. I understand that these predictions are "open-loop" prediction - no subsequent control. Is this correct ?

ANSWER	1. In fact, to "predict" a brake release time with high accuracy is very difficult. But with the integration of the AOC / Dispatch data, the "figure-of-merit" of this information will be permanently updated and become more and more accurate to close the intended brake-release time becomes target for brake-release time : $\pm$ 1 min. vs time-horizon : 4-5 minutes. 2. Yes.

NAME	D. TRIVIZAS
COMPANY	*University of Athens*
QUESTION TO	U. VÖELCKERS
TEXT	How "adaptive" is the ground movement system ?
ANSWER	As in advanced arrival management (AM) systems. If controllers use planning data and if the plan is good, it will be accepted by the controllers and adapted after a learning period.

NAME	D. TRIVIZAS
COMPANY	*University of Athens*
QUESTION TO	U. VÖELCKERS
TEXT	Is there a feed-back between planning and the active control of aircraft movements on the ground ? Is conflict-free planning of taxi-routes ensured by same conflict avoidance function (e.g. a "ground TCAS") ?
ANSWER	No ! Firstly Surface Movement Planning, allows still some planning-conflicts, because taxi operation can not be planned precisely. A certain "overlap" has to be tolerated. Otherwise the planning would be too rigid, and the real-world situation never can be controlled precisely according to his plan. Secondly, there are no defined "ground-separation-minima", between two aircraft. Separation has to be maintained by pilots based on visual information.

NAME	R.W. SIMPSON
COMPANY	MIT
QUESTION FOR	E. PETRE
TEXT	Does the European controller have the ability to reroute, change altitude, or change speed of an airborne aircraft ? How does aircraft get routed around a thunderstorm ?

ANSWER	Generally no - it requires coordination among nations. This policy is now being revised to allow this changes. By vectoring the a/c.

NAME	R.W. SIMPSON
COMPANY	MIT
QUESTION TO	E. PETRE
TEXT	Does the conflict alert function have a shorter time horizon than the surface trajectory planner horizon of 5 minutes ?
ANSWER	Yes.

SESSION 2

NAME	S. SWIERSTRA
COMPANY	EUROCONTROL
QUESTION FOR	J.F. MEREDITH
TEXT	Do you think that the cockpit crew needs to be extended to perform the ATC task. How will this additional crew be accommodated in present cockpits ?
ANSWER	No. Means need to be developed to give the existing crew awareness of the conflicting traffic principally in order that they understand, and are in sympathy with, the conflict avoidance maneuver being applied. This is so, whether the maneuver is generated by on-aircraft computers or as a result of ground based Air Traffic Management calculations.

NAME	D. TRIVIZAS
COMPANY	*University of Athens*
QUESTION FOR	J. F. MEREDITH
TEXT	How are pilots going to sense traffic around them ? (virtual reality glasses ?) What is the computational load involved ? Is this an "every man for himself" philosophy ?
ANSWER	I am sure that whatever display means are developed to give the flight deck crew situation awareness of other aircraft, it will not involve virtual reality glasses ! Whatever display has to be supported will involve a computational load which is devoted to making the data, which is available in the conflict detection process, meaningful to the flight deck crew. No it is not "every man for himself". the conflict resolutions algorithms will, wherever they are implemented.

NAME	E. PETRE
COMPANY	EUROCONTROL
QUESTION FOR	J. F. MEREDITH
TEXT	In order to support such new ATM concept, airborne equipment will be required in order : • to broadcast the a/c trajectory, and • to process the data coming from the other a/c. Can you give any indication on the availability or the underlying techniques required for such equipment ?
ANSWER	Data link communication, probably using SATCOM will be necessary whether the conflict detection and resolution is done in individual aircraft or on the ground. Datalink transmission and receiver equipment is currently being installed in aircraft being equipped for FANS1 (FANS A) operation.

NAME	A. BENOIT
COMPANY	EUROCONTROL
QUESTION FOR	J. F. MEREDITH
TEXT	You referred to "free flight" concept and, for its implementation, advocate the intense - if not the only use - of the FMS. Could you give us an idea for Continental Europe, of the difference between the actual length of flights and the corresponding great circle length for all flights over, say, a one-year period ?
ANSWER	I have seen estimates that direct routings in Europe would save about 10% of the flight length.

NAME	K. ZEGHAL
COMPANY	STERIA
QUESTION FOR	J. F. MEREDITH

TEXT

note concerning previous question :
there is a project at Eurocontrol (Freer) that aims at studying and developing an airborne separation assurance system based on trajectories and using FMS)

On one hand : flight plan optimisation for the 10 following minutes (maximal lookahead). On the other hand : a third person in the cockpit for conflict management. Where is the cost benefit ? What about reduction of route charges ?

ANSWER

I think it unlikely that conflict management would require a third crew member, but I do believe that work needs to be done on the means by which the crew will obtain good situation awareness of other aircraft in a free flight situation.

The benefit to be obtained will be the shorter path lengths flown.

NAME	A. BENOIT
COMPANY	EUROCONTROL
QUESTION TO	M. PELEGRIN

TEXT

- Causes of delay :
  .....
  .....
  ATC : 49 %, no comments
- Being here, as a member of an ATC institution, I feel to react to such a simple statement; when observing the departure board, in Brussels, a few weeks ago, you could note 11 flights announcing the same departure time !

This, obviously is included in the 49% attributed to ATC.

ANSWER

Answer to the comment....

I fully agree. A possible solution would be that large aircraft do no longer belong to a Company (but to banks !) - Large planes will be rented to Operators; several operators may occupy the same plane, offering different on-board and ground services.

NAME	H. WINTER
COMPANY	DLR
QUESTION FOR	J. K. RAMAGE
TEXT	What is the time-frame of a penetration of those military technologies for Un-manned Military Aircraft into the civilian air traffic environment ?

ANSWER

As UAV systems currently under development begin to transition to the military operational environment over the next 5 years, one can expect unprecedented increase of range performance capability to permit military operations over extremely large geographical areas.

Exploiting the full military potential of UAV will eventually require operations within the civil airspace section. Operational missions involving long range routing and/or large area loiter through civil airspace are quite conceivable within the next 5 years, including possible terminal area operation.

Next generation UAV's e.g. Unmanned Tactical Aircraft (UTA) are likely to evolve with reliable and highly automated flight path trajectory management systems, which will permit a high degree of autonomous operational capability. Technology forecast studies recently conducted by the NATO AGARD organization indicate technology maturity in the 210 to 2020 time frame.

SESSION 3

NAME	J-B. SENNEVILLE
COMPANY	FRENCH MINISTRY OF DEFENSE
QUESTION TO	R.W. SIMPSON
TEXT	You mentioned that a multi-disciplinary team requires a team leader and that so far there is no engineering course covering all the technical areas for ATM. Would you comment on the possibility of having just a "leader" with no specific engineering skills, coming from a business school for instance ?
ANSWER	I believe that any technical manager who will lead a team should understand the technical problems and trade offs. He/she will need additional training for managing a team, or an assistant who has only been to a management school to perform administrative duties for him/her.

NAME	X. FRON
COMPANY	EUROCONTROL / BRETIGNY
QUESTION TO	G. MAVRAK
REMARK	This briefing was a perfect illustration that not only engineering skills, but also organisational skills are part of ATM fundamentals

---

NAME	D. TRIVIZAS
COMPANY	*University of Athens*
QUESTION FOR	N. IMBERT
TEXT	How is the probability field selected in the simulated annealing
ANSWER	The probability is defined as $p = e^{-\Delta J/T}$ where T is the "temperature". T decreases from an initial value corresponding to $p \approx 0.5$; its variation is often made of several decreasing levels. As a result, the transitions corresponding to high worsening of the objective functions are accepted at the beginning of the process; but after, less and less objective function worsening are accepted.

NAME	H. WINTER
COMPANY	DLR
QUESTION TO	N. IMBERT
TEXT	You have presented many powerful methods of optimisation. Could you give us an impression of the different application areas of these individual methods.
ANSWER	We may roughly distinguish between the operation research type methods, which are used for planification, resource allocation flow management and control type methods : for dynamic continuous system : (trajectory computation, identification, guidance and control). The "new" methods are more general and may be used in a wide class of problems, because they make no assumption on the form of the model and criterion.

SESSION 4

NAME	E. PETRE
COMPANY	EUROCONTROL
QUESTION FOR	J. REICHMUTH
TEXT	One of the major limitations of capacity for TMA operations is what you call "precision of delivery". It has been mentioned that it is possible to land an aircraft within a few seconds. Such figures have been illustrated, e.g. a few years ago, in a paper presented by Mr Volkman Adams during an earlier AGARD symposium in Berlin. In the results presented, the mean precision of delivery ranges from 2 min. down to 40 sec. according to the various organisations. How do you explain the reasons of such evolution ?
ANSWER	(see next two questions)

NAME	C. MILLER
COMPANY	FAA - WASHINGTON DC
QUESTION TO	J. REICHMUTH
TEXT	1. Are bank angle and turn rates (via MODE-S) considered in the trajectory calculations. 2. In TMA the most important for capacity is delivery accuracy (ref. Adam) 2 min. to 40 sec. reduction ? 3.
ANSWER	(see next question)

NAME	R.W. SIMPSON
COMPANY	MIT
QUESTION TO	J. REICHMUTH
TEXT	What is 3 R's error from initial plan to touch down?
ANSWER	1. In PD2 all « points » of the trajectory are down-linked from whichone can calculate the arrivals manager rates 2. There are several reasons: there were 5 conflicts which controllers have to solved manually, also pseudo-pilots mistakes and advisory were not updated; therefore the achieved level was low compared to Adam's values 3. Yes they are

---

NAME	C. MILLER
COMPANY	FAA - WASHINGTON DC
QUESTION FOR	J. REICHMUTH
TEXT	In the development of the arrival manager has consideration been given to downlinking aircraft bank angle, turn rate, vertical rate and/or other state variables as a means for improving the ability of the arrival manager to monitor aircraft conformance to flight plan ? Do you believe that downlinking state variables would improve the performance of the arrival manager ?
ANSWER	The Arrival Manager uses the downlinked trajectory information. From this, bank angle, turn rate and other state variables can be derived. Monitoring aircraft's conformance to flight plan is the task of the Flight Path monitor (FPM) within the PHARE concept. I believe that downlink of the state variables would improve the performance of the FPM (and also the Controller's in conformance monitoring).

NAME	E. PETRE
COMPANY	EUROCONTROL
QUESTION TO	N. DURAND
TEXT	The problem resolution approach presented seems to be on the tactical level, while people generally consider Problem Solving more on a planning level. As this "short-time" notice seems indeed to be embedded in your approach, how do you see possible implementation of such tool ?
ANSWER	First of all, such a tool could be used to help controllers to make a choice as genetic Algorithms are able not only to find the global optimum but a set of good solutions that have different characteristics. In order to let controllers enough time to react in case pilots or FMS do not follow exactly maneuver orders given to them (or it), we should probably adapt the separation function l instead of considering a fixed standard separation in nautical miles, we should consider a time to collision (or conflict) standard separation

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NAME	C. GARCIA AVELLO
QUESTION TO	K. .ZEGHAL
TEXT	When the crossing problem is solved with the "coupled sliding forces", the solution (perturbations) is note equally distributed. Why ?
ANSWER	Because one of the force is directed along the velocity vector, whereas the other is normal to the motion. The heading change for the first one is therefore very low.

NAME	A. DEDRYVERE
COMPANY	DNA FRANCE
QUESTION TO	K. ZEGHAL
TEXT	• Does this method assume the same algorithm in all aircraft ? • What happens if not ?
ANSWER	Basically, yes it does. If the intruder has a different algorithm, the avoidance maneuver are not guaranteed to be coherent. some solutions can be envisaged to overcome this limitation.

NAME	J. REICHMUTH
COMPANY	DLR
QUESTION TO	K. ZEGHAL
TEXT	Are you sure to find always a solution also in case of more than two are involved ?
ANSWER	Some typical encounters involving more than 2 a/c have been created to test the logic : the logic behaves properly and finds a solution. Some results concerning density can be found in the first reference indicated in the paper. However, there is a maximal density : 30 a/c with a lookahead of 2 minutes is probably unsolvable.

SESSION 5

NAME	J. REICHMUTH
COMPANY	DLR
QUESTION TO	N. GALANTAI
TEXT	Is there an "undo" function provided in the system, to allow to correct mistakes / wrong data entries.
ANSWER	Yes, but only for the "back-transfer" of aircraft that have been handed-over, for example for aircraft, which revoke e.g. their start-up. But not to "undo" wrong data entries, which can be corrected by over-writing with the correct data.

NAME D. TRIVIZAS

COMPANY *University of Athens*

QUESTION TO N. GALANTAI

TEXT

HMI IN MATIAS

The design included an exhaustive enumeration of windows.
I would like to know what are the design principles, methodology and objectives.

ANSWER

Objective

To implement a cost-effective ATM system, which is capable to cope with the current and expected traffic demand in 2003 and which is in line with EATCHIP.

Design principles
- the system shall be safe, easy to handle and expandable
- in order to provide a relative easy change-over the task of the controllers should not change significantly
- the system has to eliminate current deficiencies
- shipless system
- easily modifiable HMI

Method
- analyzing current domestic system and working methodology
- analyzing currently used HMI in foreign countries and planned implementations
- designate roles and tasks in the new system
- significant involvement of the future users (controllers) in the design and testing.

NAME	H. WINTER
COMPANY	DLR
QUESTION TO	C. MILLER

TEXT

How does this method of planning the R&D work of FAA work in the case where the result of the research is still far away from successful application like in the case of Wake Vortex research

ANSWER

Comment : R.W. SIMPSON
The wake vortex research should be pursued in the context of the benefits (outcomes) that agency customers may experience as a result. For example, the purpose of the research may be to determine the feasibility and technical approach for a dynamic wake vortex advisory system for arriving aircraft. The system would operate with an arrival traffic manager to automatically reduce aircraft spacing when vortices are note a hazard due to favorable atmospheric condition (cross winds, turbulence) When conditions are less favorable, the spacing would be increased. overall, the benefit would be increased airport capacity. It is possible that the research would determine that such a system is not practical. Ever so, the investment in the research would have been focused on specific benefits for customers.

Investments in ATM R&D that are not linked to specific foreseen benefits for system customers are difficult to justify. A single exception may be R&D for the purpose of better understanding the current and future ATM processes and the R&D that is needed to advance the progress of the system.

NAME	M. PELEGRIN
COMPANY	ANAE
QUESTION TO	A. DEDRYVERE

TEXT

Will the ATN use ground commercial networks for links between ground centers ? If yes, what about protocols ?

ANSWER

Yes.
ATN (in its network and transport layers) will accept a big variety of subnetworks accepting ISO protocols =

- X25 public data networks and later Asynchronous transfer mode
- X25 ATC dedicated networks
  (i.e. = RAPNET of Eurocontrol
  RENAR of France
  REDAN of Spain)
- SITA network with adequate protocols
- (i.e. the "data 3") etc.

NAME	E. PETRE
COMPANY	EUROCONTROL
QUESTION TO	A. DEDRYVERE
TEXT	I was surprised by your sentence : "ATN is a private internet" Do we have to understand that ICAO will in the future support an alignment of ATN to internet developments ?
ANSWER	Consider "internet" or "internetworking" as a general purpose words. ATN is a federation of subnetworks, some of them are mobile. It is an <u>operational</u> network with quality of services constraints that the famous Internet (with capital I) has not.

NAME	A. BENOIT
COMPANY	EUROCONTROL
QUESTION TO	A. DEDRYVERE
TEXT	In the early 70's, MLS was strongly advocated by the US-FAA. You showed what happened. Didn't Russia have a plan for implementing MLS ?
ANSWER	Various countries hesitate between implementing MLS or waiting the availability of GNSS + Local Area Augmentation System. UK (in Heathrow) and NL (in Amsterdam) have wave-reflection problems for ILS (buildings) and may be can not wait - Russia ?

SESSION 6

NAME	M. PELEGRIN
COMPANY	ANAE
QUESTION TO	many speakers
TEXT	The importance of color codes which appear on the screens has been mentioned by many authors since yesterday. When a controller is engaged, does he has a detailed color blindness test ?
ANSWER	R.W. SIMPSON : I hope so !

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14. Abstract

Over the past 25 years, the Guidance and Control Panel and now the Mission Systems Panel of the Advisory Group for Aerospace Research and Development to the North Atlantic Treaty Organization have devoted part of their activities to the fascinating field known historically as Air Traffic Control, but covering most facets of Air Traffic Handling.

This Workshop, organized as a contribution to the increasing cooperation between the NATO Nations and former Warsaw Pact European countries, was intended to be complementary to the numerous conferences addressing the management of Air Traffic Handling.

This volume contains the 19 papers presented at the Conference under the session headings:
- Air Traffic Handling: A Large-Scale;
- International, Multidisciplinary and Complex System;
- The Aircraft: The Basic Element of Air Traffic;
- Air Traffic Management: Fundamentals;
- Examples of Application;
- Plans and Prospectives.

The main Session discussions are also included, and so is a summary of the activities conducted by the Guidance and Control Panel and the Mission Systems Panel in Air Traffic Handling.

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